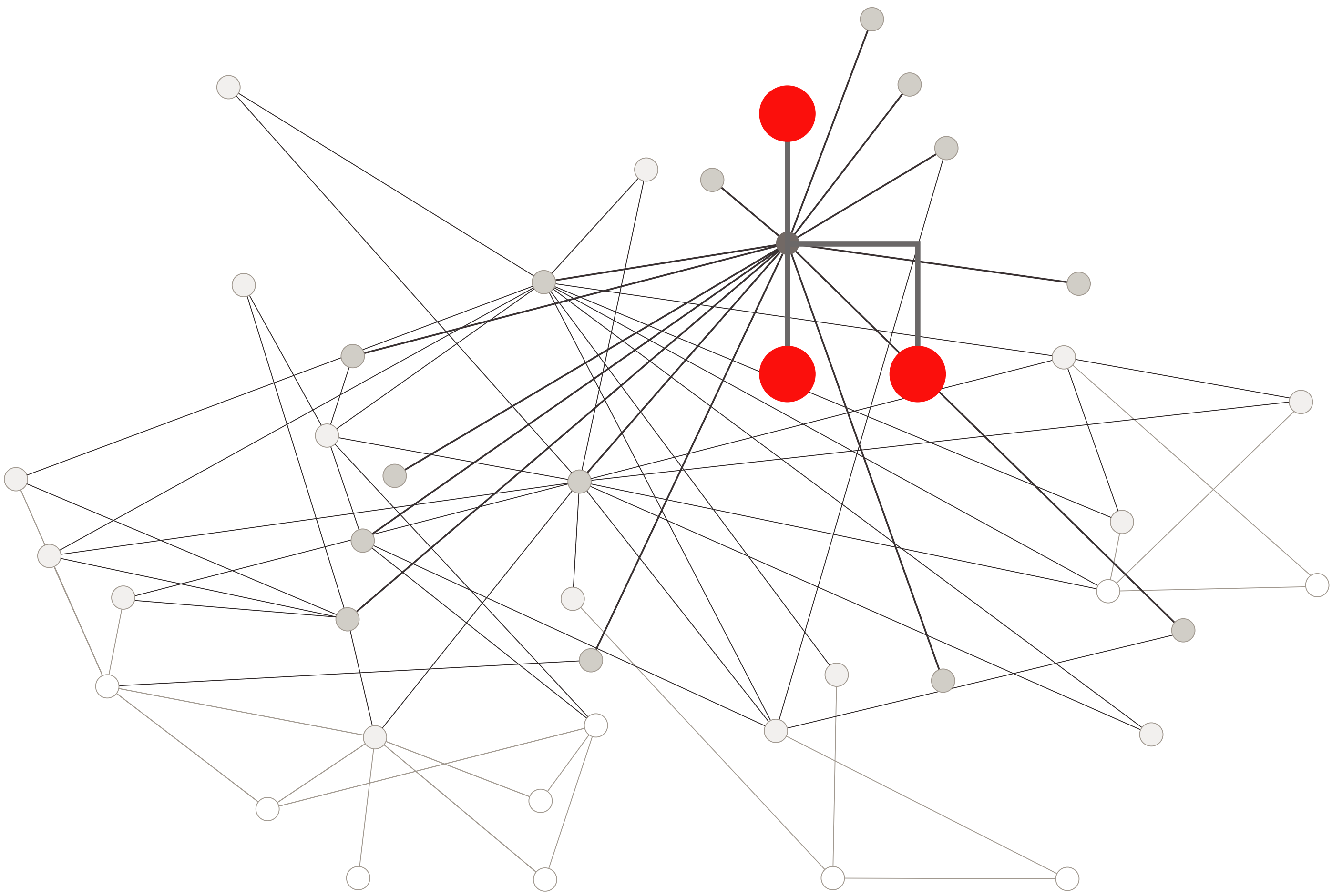

A Computational Study on Form

a Grammar-based Tool for Multipurpose Chair Design

Sara Filipe Lopes Garcia

Orientador: Doutor Luís António dos Santos Romão

Doutoramento em Design 2018

Tese especialmente elaborada para a obtenção do grau de doutor

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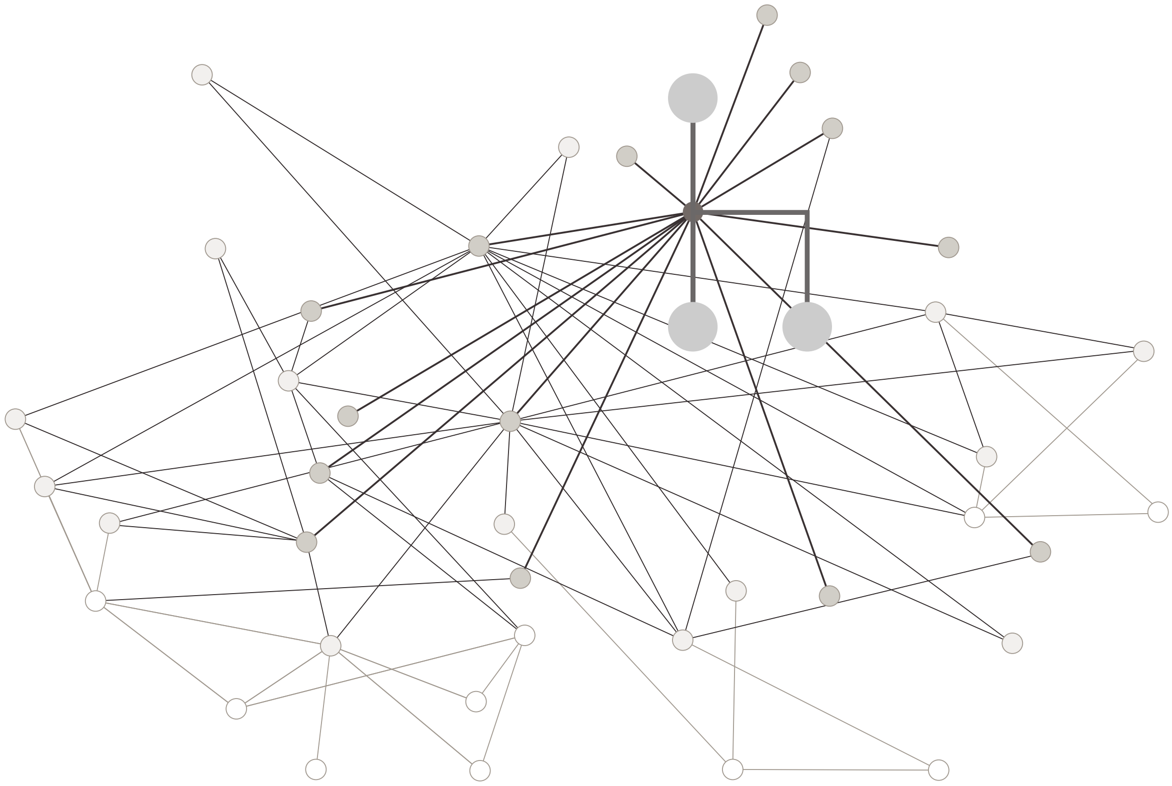

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Volume I

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"*O caos é uma ordem por decifrar*"

Chaos is order yet undeciphered

José Saramago[1]

[1] Saramago, J 2002, O Homem Duplicado, Caminho, Lisboa.

ABSTRACT

The individuals of a class reveal an apparent formal chaos, yet within such differences amongst them, similar characteristics can be identified. The study of form through ontological and formal approaches provides a means to systematize the underlying rules which (de)codify the formal diversity inherent to a class. Such approaches are contemplated by computational design, which enables a mathematical description and generation of complex designs, by using simple rules. However, currently available computational design tools are typically restricted to solution spaces corresponding to design styles or product families. Moreover, they are still mostly utilised as proof of concept which leads to limited practical application, particularly within the earlier phases of the design process.

In order to build upon such shortcomings, the main goal of this research is to develop a computational model capable of, firstly, describing and generating a large number of design types within one product class; and, secondly, having a practical application as a design tool for the early concept phase of the design process.

The development of the computational model was based upon a methodology structured into six sequential stages: (1) plan – the planning of the requirements and the definition of the product class; (2) sample – the selection of a set of designs representative of the product class; (3) ontology – the development of a formal ontology which is able to describe design parts and their relations and properties; (4) grammar – the development of an ontology-based shape grammar, able to describe and generate designs within the specified product class; (5) implementation – the translation of the shape grammar into a digital environment; and, (6) evaluation – the assessment of the usability and usefulness of the implementation by design students and practitioners. Such methodology was applied to the product class of multipurpose chairs, as a case study.

The major outcome of this research is translated into a grammar-based design tool for the concept phase of multipurpose chair design. The tool enables the generation of designs through the addition/deletion of the chair parts and the manipulation of their parameters, while ensuring the necessary restrictions imposed by anthropometric standards. Throughout this study, the construction of the tool has been orientated towards generating a large variety of designs within a product class – which ultimately, is argued to have a practical application in real-life design scenarios.

Keywords

Study of Form; Computational Design; Shape Grammars; Design Tools; Multipurpose Chairs

RESUMO

Os indivíduos de uma classe revelam um aparente caos formal; contudo, apesar das diferenças entre eles, há características semelhantes que podem ser identificadas. O estudo da forma, através de abordagens ontológicas e formais, proporciona um meio de sistematizar as regras subjacentes que (des)codificam a diversidade formal inerente a uma classe. Essas abordagens são contempladas pelo design computacional, que permite uma descrição e geração matemática de resultados complexos, através do uso de regras simples. Contudo, as ferramentas computacionais de design disponíveis actualmente são tipicamente limitadas a espaços de solução consignados a estilos de design ou famílias de produtos, e são ainda usadas maioritariamente como uma prova de conceito, o que resulta numa aplicação prática limitada principalmente nas fases iniciais do processo de projecto.

De modo a actuar sobre estes pontos fracos, o objectivo principal desta investigação é desenvolver um modelo computacional capaz de, em primeiro lugar, descrever e gerar um grande número de tipos de soluções dentro de uma classe de produtos, e, em segundo lugar, providenciar uma aplicação prática como ferramenta de projecto destinada às fases iniciais de conceito do processo de projecto.

O desenvolvimento do modelo computacional baseou-se numa metodologia composta por seis etapas sucessivas: (1) plano – planeamento dos requisitos e a definição da classe de produtos; (2) amostra – selecção de um conjunto de objectos representativos de uma classe de produtos; (3) ontologia – desenvolvimento de uma ontologia formal, capaz de descrever as partes de um produto, as suas relações e propriedades; (4) gramática – desenvolvimento de uma gramática da forma baseada em ontologias, capaz de descrever e gerar soluções dentro da referida classe de produtos; (5) implementação – tradução da gramática da forma para um ambiente digital; e (6) avaliação – aferição da usabilidade e utilidade da implementação por estudantes e profissionais de design. Esta metodologia foi aplicada à classe de produtos das cadeiras multiuso, como caso de estudo.

O principal resultado desta investigação traduz-se numa ferramenta de projecto baseada em gramáticas, destinada à fase de conceito do projecto de cadeiras multiuso. A ferramenta permite a geração de soluções através da adição e subtracção das partes da cadeira e da manipulação dos seus parâmetros, assegurando as restrições necessárias dadas pelas normas antropométricas. Por meio deste estudo, a construção da ferramenta foi orientada de modo a gerar uma grande diversidade de soluções dentro de uma classe de produtos, o que, em última instância, se argumenta ter uma aplicação prática em situações reais de projecto.

Palavras-chave

Estudo da Forma; Design Computacional; Gramáticas da Forma; Ferramentas de Design; Cadeiras Multiuso

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ACRONYMS AND ABBREVIATIONS

2D	Two-Dimensional space
3D	Three-Dimensional space
AI	Artificial Intelligence
ANSI	American National Standards Institute
BIFMA	Business and Institutional Furniture Manufacturers Association
CAD	Computer-Aided Design
CAE	Computer-Aided Engineering
CAM	Computer-Aided Manufacturing
CEN	European Committee for Standardization
CNC	Computer Numerical Control
DCG	Daciano Chair Grammar
Def.	Default
DJCG	Daciano-Jasper Common Grammar
DJHG	Daciano-Jasper Hybrid Grammar
DM	The Design Museum
DNA	Deoxyribonucleic Acid
E1	First Evaluation
E2	Second Evaluation
FDM	Fused Deposition Modelling
Fi	Irreproducible Features
Fr	Reproducible Features
GUI	Graphical User Interface
ICG	Iconic Chair Grammar
ID	Identification
INC	Incomplete
ISO	International Organization for Standardization
JCG	Jasper Chair Grammar
LHS	Left-Hand Side
MCG	Multipurpose Chair Grammar
MoMA	Museum of Modern Art
MUDE	Museu do Design e da Moda
N/A	Not Applicable
NIOSH	National Institute for Occupational Safety and Health
RHS	Right-Hand Side
SCG	Synthetic Chair Grammar
SD	Standard Deviation
SG	Shape Grammar
TCG	Thonet Chair Grammar
UNK	Unknown
V&A	Victoria & Albert Museum
VDM	Vitra Design Museum
WxDxHxSH	Width x Depth x Height x Seat Height

Rule Acronyms

AG	Arm Guides
AP	Arm Panel
AR1	Armrest 1
AR2	Armrest 2
AR3	Armrest 3
AR4	Armrest 4
ASB1	Arm Support Back 1
ASB2	Arm Support Back 2
ASB3	Arm Support Back 3
ASB4	Arm Support Back 4
ASB5	Arm Support Back 5
ASF1	Arm Support Front 1
ASF2	Arm Support Front 2
ASF3	Arm Support Front 3
ASF4	Arm Support Front 4
ASS1	Arm Support Side 1
ASS2	Arm Support Side 2
ASS3	Arm Support Side 3
BB	Back Bottom
BC	Back Cross
BG	Back Guides
BP	Back Panel
BR1	Back Radial 1
BR2	Back Radial 2
BS1	Back Splat 1
BS2	Back Splat 2
BS3	Back Splat 3
BS4	Back Splat 4
BS5	Back Splat 5
BT1	Back Top 1
BT2	Back Top 2
BT3	Back Top 3
BT4	Back Top 4
BU1	Back Upright 1
BU2	Back Upright 2
BU3	Back Upright 3
LB	Leg Back
LF	Leg Front
LG	Legs Guides
LPB1	Leg Panel Back 1
LPB2	Leg Panel Back 2
LPF1	Leg Panel Front 1
LPF2	Leg Panel Front 2
LPR	Leg Panel Radial
LPS	Leg Panel Side
LBB1	Leg-Base Back 1
LBB2	Leg-Base Back 2
LBB3	Leg-Base Back 3
LBC1	Leg-Base Cross 1
LBC2	Leg-Base Cross 2
LBF1	Leg-Base Front 1
LBF2	Leg-Base Front 2
LBF3	Leg-Base Front 3
LBG	Leg-Base Guides
LBL1	Leg-Base Long 1
LBL2	Leg-Base Long 2
LBL3	Leg-Base Long 3
LBL4	Leg-Base Long 4
LBL5	Leg-Base Long 5
LBP	Leg-Base Panel
LBR1	Leg-Base Radial 1
LBR2	Leg-Base Radial 2
LBR3	Leg-Base Radial 3
LBS1	Leg-Base Side 1
LBS2	Leg-Base Side 2
LBS3	Leg-Base Side 3
LBS4	Leg-Base Side 4
LSB1	Leg-Stretchers Back 1
LSB2	Leg-Stretchers Back 2
LSC1	Leg-Stretchers Cross 1
LSC2	Leg-Stretchers Cross 2
LSF1	Leg-Stretchers Front 1
LSF2	Leg-Stretchers Front 2
LSG	Leg-Stretchers Guides
LSL1	Leg-Stretchers Long 1
LSL2	Leg-Stretchers Long 2
LSL3	Leg-Stretchers Long 3
LSL4	Leg-Stretchers Long 4
LSL5	Leg-Stretchers Long 5
LSP	Leg-Stretchers Panel
LSR1	Leg-Stretchers Radial 1
LSR2	Leg-Stretchers Radial 2
LSS1	Leg-Stretchers Side 1
LSS2	Leg-Stretchers Side 2
LSS3	Leg-Stretchers Side 3
MSF-SR	Mode-Solid Frame Section Round
MSF-SS	Mode-Solid Frame Section Square
MSP	Mode-Solid Panels
SB1	Seat Back 1
SB2	Seat Back 2
SC1	Seat Cross 1
SC2	Seat Cross 2
SF1	Seat Front 1
SF2	Seat Front 2
SG	Seat Guides
SL1	Seat Long 1
SL2	Seat Long 2
SL3	Seat Long 3
SL4	Seat Long 4
SL5	Seat Long 5
SP	Seat Panel
SR1	Seat Radial 1
SR2	Seat Radial 2
SR3	Seat Radial 3
SS1	Seat Side 1
SS2	Seat Side 2
SS3	Seat Side 3
T	Termination

GLOSSARY

Analytic Grammar: a *shape grammar* developed upon the analysis of a *design corpus* from an underlying existing *design language*, generating existing and new *designs* within the language

Chair: object whose function is to support the human body in a sitting position (offering support for the thighs and the back); movable and for individual usage

Class: an abstract concept which groups individuals (or instances) with similar characteristics; an *ontology* component (e.g., 'multipurpose chair'; 'leg')

Common Grammar: a grammar which results from the intersection of two or more *specific grammars* ('common' is not to be confused with 'standard')

Complement Grammar: a grammar which results from the complement of a *specific grammar* in relation to a *generic grammar*

Computational Design: the use of mathematical or logical reasoning to address a design problem

Computational Model: a mathematical description of an entity, a system, or a process (typically based on a schematic representation)

Computer-Aided Design (CAD): *digital design* tools based on graphic representations (e.g.: digital drawings or digital models)

Convenience Sample: a sampling method comprising the selection of the most accessible sample, in order to save resources (Marshall 1996)

Design: an individual object or artefact, or the description of something that is to be realised (including graphical and textual representations); the term may also refer to the *design process*

Design Algebra: a notation that describes set of entities that carry out computations used in a design domain; for instance, a *shape grammar* is defined in shape algebra, comprising a set of basic elements arranged in a space of n dimensions

Design Collection: a set of designs comprising different functions but sharing a similar style, intended to be used together (e.g. a furniture collection including chairs, stools, and tables)

Design Corpus: a set of existing *designs* that are used as a reference for the development of an *analytic grammar*

Design Derivation: the step-by-step generation of a *design* after *rule* applications

Design Family: a set of designs sharing a similar function but having slight different appearances, due to variations in colour, material, finishing, or interchangeable parts (e.g. chairs Thonet 214, 215, and 218)

Design Grammar: a *shape grammar* whose application relies in the scope of design domains, such as product design, architectural design, or urban design

Design Language: the set of all *designs* generated by a *shape grammar*, characterizing for e.g. a style, a brand, a product class or a design collection

Design Phase: each stage of the design process: (1) research: problem analysis and reformulation through the research of relevant information; (2) concept: generation, evaluation and selection of ideas; (3) development: refinement and testing of the selected ideas; (4) detail: complete definition of the final solution; and (5) production: product manufacturing

Design Process: the set of actions, methods and resources employed in the progression between a design problem and a design solution

Design Style: a context-dependent category, characterizing a group of objects that are related to a period (period style – e.g. Queen Anne style), a place (regional style – e.g. Italian design), a person (individual style – e.g. Hepplewhite style) or a group of persons (group style)

Design Sub-Language: a subset of a *design language*

Design Tool: a device intended to aid designers in the accomplishment of a given design task; tools can comprise methods (e.g. drawing), objects (e.g. pencils), or software (e.g. *CAD*)

Design Type: a context-independent category, characterizing a group of objects that share a given function (e.g. multipurpose chair), morphology (e.g. cantilever chair), material (e.g. wooden chair) or shape (e.g. S-shaped chair)

Design Vocabulary: the basic building elements of a *design* (e.g. parts of a *chair*)

Digital Design: computer-implemented *computational design*

Domain: an area of discourse addressing the knowledge of a particular field, subject or discipline (e.g. design domain)

Emergence: the ability to recognize and use something that is not predefined but is made explicit during a process, such as emergent shapes (which in *shape grammars* are derived from the decomposition of shapes), emergent meanings, and so forth

Form: a board term encompassing different meanings: the configuration of parts (structural form); the perceived external form (apparent form); the visual appearance comprising *shape*, colour and texture (outline form); an abstract concept or archetype that is revealed in particular objects (substantial form); or a mental concept (*priori* form)

Generative Design: the use of computational processes to describe and generate *designs*

Generic Grammar: a grammar that contemplates multiple *design sub-languages* among a more general *design language*, comprising an extension of rules, parameters and/or deletion of labels of a more *specific grammar*

Hybrid Grammar: a grammar which results from the union of two or more *specific grammars*

Initial Shape: in *shape grammar*, is the starting shape from which the *rules* are applied

Judgment Sample: a sampling method comprising the selection of the most effective sample to answer a given research question, based on the researcher's knowledge and literature review (Marshall 1996)

Meta-Ontology: an ontology corresponding to a superset of another ontology, addressing a more generic *domain*

Meta-Grammar: a grammar corresponding to a superset of another grammar; different types of meta-grammars can be considered (e.g. *generic grammar* and *hybrid grammar*)

Modern Chair: a *chair* designed in the period between 1850 and the present

Multipurpose Chair: a *chair* that is suitable for several purposes, spaces, users, and situations

Ontology (computation): a formalism to represent knowledge within a domain, through a definition of *classes*, properties (attributes) and relations (Gruber 1993)

Parametric Grammar: a *shape grammar* whose rules are composed by shape schemas, which describe a set of topologically identical shapes defined by variables; when values are assigned to those variables, a *shape* is obtained

Population: a general (and potentially infinite) group of individuals sharing certain characteristics, which is under consideration of a certain study

Product Version: a product that corresponds to an upgrade or adaptation of a previously designed product (e.g., chairs Thonet No. 14 and 214)

Rule: a production rule from the type Left-Hand Side (LHS) → Right-Hand Side (RHS); in a *shape grammar* both LHS and RHS are shapes (the RHS can be an empty shape)

Sample: a group of individuals (or instances) that participates in a study, selected from a given *subpopulation* according to a certain sampling criteria

Set Grammar: a *shape grammar* where rules are composed by indecomposable shapes, and thus can be represented by symbols

Shape: is one of the *form* properties (it does not have size, colour, texture, or meaning); in a *shape grammar*, is a finite but possibly empty set of basic elements (points, lines, planes, and solids)

Shape Grammar (SG): a formalism to describe and generate *designs*, through if-then shape rules (Stiny & Gips 1972); an SG is composed by an *initial shape*, a set of *rules*, a set of decomposable *shapes*, and a set of labels, and it defines a *design language*

Specific Grammar: a grammar that contemplates one *design language*, comprising a restriction of rules, parameters and/or addition of labels of a more *generic grammar*

Shape Grammar Implementation: the translation of a *shape grammar* into a digital environment, by using a *shape grammar interpreter* or by creating a specific implementation

Shape Grammar Interpreter: a computer program that compiles a *shape grammar* and produces results, allowing users to implement and use different shape grammars

Spiral Model: an iterative and incremental model for software development, composed of a set of sequential *stages* which are revisited in several *product versions* (Boehm 1986)

Stage: a sequential part of a model or methodology, comprising particular goals, methods, tasks and actions

Step: a procedure from a sequence of actions (e.g. the application of a *rule* to a *shape*)

Sub-Grammar: a grammar corresponding to a subset of another grammar; different types of sub-grammars can be considered (e.g. *specific grammar* and *common grammar*)

Subclass: a subset of a class (e.g., ‘multipurpose stacking chair’ is a subclass of ‘multipurpose chair’; ‘front leg’ is a subclass of ‘leg’)

Subpopulation: a subset of a *population*, constituted by a delimited group of individuals that could possibly participate in a study (the term is also called study population)

Synthetic Grammar: a *shape grammar* developed by synthetic processes from a given *design vocabulary*, generating a new *design language*

Theoretical Sample: a sampling method comprising an iterative process between the elaboration of a theory and the sample selection (Marshall 1996)

Transformation Grammar: a *shape grammar* developed from the transformation of a given grammar, generating other existing or original *design languages*

1

Introduction

1 INTRODUCTION

This introductory chapter defines the concerns, approaches and methodologies employed in this research. The research background, the research problem, the research goals and the research questions are described. The hypothesis and the research methodology employed to test it are presented. The significance of the study is clarified. Finally, the structure of the thesis is specified through a brief summary of each chapter.

1.1 Research Background

This thesis carries the title *A Computational Study on Form: a Grammar-based Tool for Multipurpose Chair Design*. This research is focused on the study of form following a computational approach, i.e., employing mathematical or logical methods. Computational approaches provide a means to study the form in the light of creation, evolution, and transformation. Moreover, complex and diverse forms can be described and generated by simple underlying rules. The motivation of this research is to describe and generate in a systematic way the formal diversity inherent to one product class. For that purpose, the multipurpose chair class was selected as a case study. The practical applicability of this research relies on a grammar-based design tool for the concept phase of chair design.

The background of this research includes the definitions of form, an overview of studies on form following a mathematical approach, and its possible applications to design domains.

1.1.1 Definitions of Form

The word *form* derivates from the Latin *forma*, which combined the meanings of the two Greek words μορφή (*morphē*) and εἶδος (*eidos*). The first term refers to the visible forms and the second term to the conceptual forms (Tatarkiewicz [1976] 2001). Although this early definition is closely related to the philosophical approach, the term has several meanings, varying according to the application domain (e.g. philosophy, psychology, biology, mathematics, art and design). Tatarkiewicz [1976] (2001) synthesized five main definitions of form, which are addressed by different authors:

A) *Structural Form*: is the internal structure of an entity, i.e., the invisible skeleton, given by the configuration of the parts within the whole (Wong 1993). This concept was formulated in the Pythagorean School, where the form was described by numbers and the beauty resulted from order and proportion between the parts. This approach was largely employed by architects, from Vitruvius to Le Corbusier. The form as the result of internal natural forces is a concept used in biology (Thompson [1917] 1942) and adopted by architects (Alexander 1964).

B) *Apparent Form*: is the appearance of an entity, resulting from the perception through the senses. The sophists were the first to distinguish the form (B) from the content; i.e.; from external form to internal meaning. There are two types of form B: figurative form (representational, comprising a meaning) and abstract form (not comprising a meaning). The form as the result of perception is largely studied in the Gestalt psychology (Arnheim [1954] 1974).

C) *Outline Form*: is the external shape of an entity, given by its boundaries or its outer surfaces. The term shape, commonly employed in visual arts, is often used as a synonym of form. However, the terms have different meanings. According to Wong (1993), form is the visual appearance of an entity, and comprises shape, size, colour and texture. Form is three-dimensional, has a volume and a location in space. The shape is one of the form properties, and is defined by a boundary. The shape may be two-dimensional (e.g. circle, square, and triangle) or three-dimensional (e.g. sphere, cube, and pyramid). The shape does not have size, colour or texture. It may be regarded as an abstraction of form (e.g. the form of a "ball" has a spherical shape).

D) *Substantial Form*: is the conceptual form, the metaphysical essence of an entity that is revealed in matter. This philosophical concept was discussed by both Plato and Aristotle, relying in the duality between Form and Matter (abstract/concrete). In the theory of forms of Plato, the Form belongs to the abstract and intelligible world of ideas, and is real, atemporal, immutable and perfect; while the Matter belongs to the material and sensitive world, and is unreal, ephemeral, mutable and imperfect. The Matter mimics the ideal Form without never achieving its perfection; for e.g., the conceptual Form of the circle is perfect and immutable, unlike a drawn circle, which is imperfect and mutable. Unlike Plato, Aristotle denied the existence of the Form as an independent world. He believed that everything is composed by both Form and Matter. In his theory of the universals, Aristotle says that a universal entity (the substantial Form or archetype) can be represented in several particular entities (the accidental Form or Matter). For e.g., the universal concept *chairness* is the essence of the chair that makes any chair to be a chair, and is applicable to every particular chair. This definition of form is valid not only for objects but also for qualities such as colours, beauty and happiness.

E) *Priori Form*: is the mental conceptual form. Unlike the former theories of form D, Kant defended that the form is not real; it is a product of each one's mind. Kant rejects the existence of an objective world. He believed that the form is a result of experience, and is imposed by an individual on material objects.

1.1.2 Studying the Form

Since thousands of years ago mankind shows a fascination concerning the understanding of form. Philosophers, biologists, mathematicians, geometers and architects have been searching for the principles that rule the forms of our world, searching for the reason of why things have a certain form and why they evolve in a certain way, searching for the most perfect and harmonious forms, and searching for methods for generating complex forms. These studies ultimately assume that our apparent complex and chaotic world can be systematically described.

The study of abstract, natural (living and non-living) and artificial forms reveals an underlying beauty which is believed to be driven from mathematical principles. Mankind has early on shown an obsession with symmetric regular forms. The five platonic solids (**Fig. 1.1**, left) are the only possibilities of having equal faces meeting at the same angle. The Greek philosopher Plato believed that those perfect shapes could describe the whole world. In fact, these solids can be found in the middle of intersecting soap bubbles (e.g. twelve bubbles form a dodecahedron), in salt crystals (cube) and in virus particles (icosahedrons). These solids are a result of the rule of nature of always trying to find the most efficient shape. Another example of this rule are hexagonal patterns – the regular tiling that uses the least amount of material, which can be observed in beehives (Sautoy 2011). Ancient architects used harmonious shapes, proportions and symmetry which they believed to be sacred, in the design of monuments, temples, churches and palaces. The golden section is claimed (Ghyka [1946] 1977) to be visible in several natural forms, such as the Nautilus shell (**Fig. 1.1**, centre), and in many monuments of antiquity, such as the Great Pyramid in Egypt, the Parthenon in Greece, and the Pantheon in Rome (**Fig. 1.1**, right).

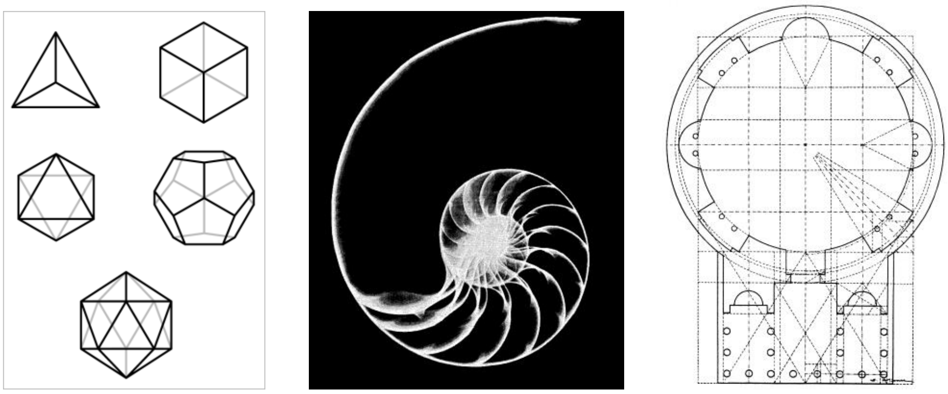

Fig. 1.1 Sacred form: the five Platonic Solids – left; the golden section in the Nautilus shell – centre (Ghyka [1946] 1977, p.101) and the golden section in the Pantheon of Rome – right (Ghyka [1946] 1977, p.147)

Our world exhibits has an enormous formal variety, apparently inexplicable. Several studies in different domains, including biology, art and architecture, aim at (de)codifying[1] that diversity following a mathematical approach. The study of the variety of natural or artificial forms can made through a perspective of time, in an evolutionary approach. For example, Darwin [1859] (2006) found that the size and shape of the bird's beaks evolved to adapt to different types of food – **Fig. 1.2**, left, and Basalla (1988) studied the technological evolution of several types of artefacts – **Fig. 1.2**, right.

[1] The term (de)codify is used to contemplate two possibilities: (i) decode, i.e., to discover the code (assuming that there is a code inherent to all things, such as the one present in DNA); and (ii) encode, i.e., to find a code (assuming that something can be explained by one or more hypothetical codes).

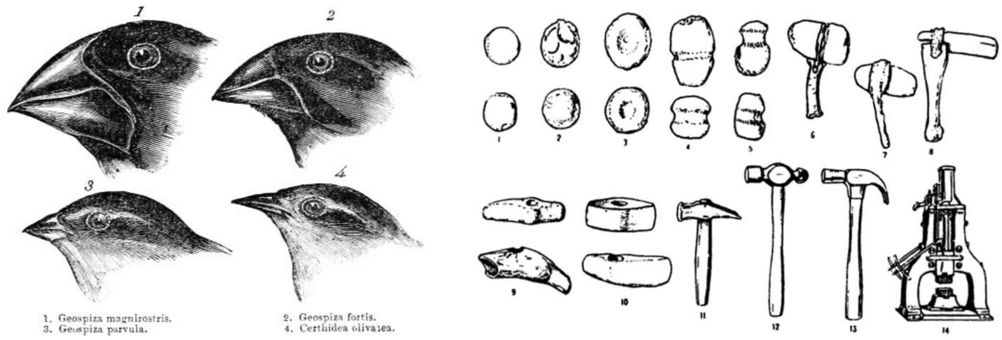

Fig. 1.2 Form evolution: bird's beaks – left (Darwin [1860] 2009, p.322) and hammer – right (Basalla 1988)

Form can also be studied through mechanisms of transformation. Simple geometric transformations can explain differences in related species, such as humans – **Fig. 1.3**, left (Dürer [1532] 2003) and fishes – **Fig. 1.3**, centre (Thompson [1917] 1942). The transformation of forms can be used as a generative procedure. For instance, architects use physical models to deform ruled surfaces, as observed in **Fig. 1.3**, right (Otto et al. [1995] 2001).

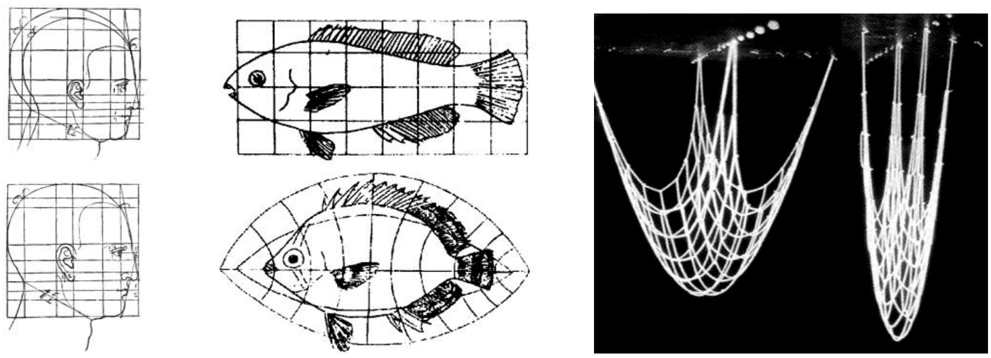

Fig. 1.3 Form transformation: man's head – left (Dürer [1532] 2003), fishes – centre (Thompson [1917] 1942, p.1062), and chain net suspension models – right (Otto et al. [1995] 2001, p.137)

Nature, apparently complex and chaotic, is composed of hidden patterns that can be described through mathematics. The apparent randomness of chaotic systems, such as trees, hides an underlying self-similar pattern, which can be simulated by fractals. The growth of the branches is ruled by a fractal property in order to maximize the sunlight it obtains, and it is also influenced by unpredictable environmental circumstances, such as wind, natural accidents and growing seasons. A single rule (grow and divide) used iteratively can simulate the complex shape of a tree (**Fig. 1.4**, left). Fractals can not only be found in nature but also in manmade forms, such as in Pollock's paintings (Sautoy 2011), as illustrated in **Fig. 1.4**, right.

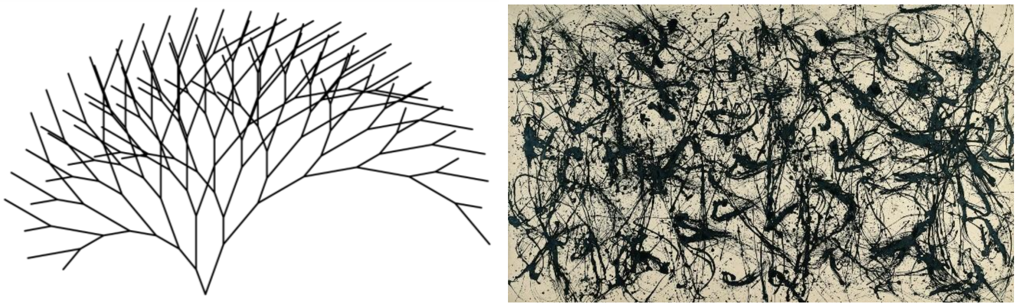

Fig. 1.4 Fractals: tree curve – left (Becker & Dorfler 1989); and painting Number 32 – right (Pollock 1950)

Sautoy (2011) believes that there is an underlying code that explains all the shapes of our apparently chaotic and complex world; a code that is composed by simple mathematical rules:

> *"Despite of the incredible complexity of the world we live in, it can all ultimately be explained by numbers"(Sautoy 2011, p.56:54).*

The most powerful evidence of such a code is found in DNA, a molecule that exists in the cells of every living organism. DNA encodes the similarities and differences that characterize a species. Species exhibit an apparent formal chaos on a micro-scale, since they have distinctive characteristics (such as the eye colour) which make every individual unique. However, on a macro-scale, they all share similarities (such as the number of eyes). DNA is composed by the same elements (the bases A, C, T, G), arranged in a unique sequence for each individual. That sequence will determine its specific characteristics, such as height, eye colour, and blood type. The complete sequence of DNA is called a genome; the human genome contains around three billion pairs of bases. An individual share 99.9% of his/her sequence with other human beings, thus 0.1% of the sequence will specify its unique features (Henderson 2009).

1.1.3 Computational Design

The study of form following a mathematical approach has a wide application in design domains. Form is the most obvious result of any design process: "the ultimate object of design is form" (Alexander 1964, p.15). The study of form is intricate, since it is related to several factors, such as function, space, time, colour, beauty, taste, and imagination (Saarinen [1948] 1985). The form can be a product of different factors, as expressed in the statements: form follows function (Sullivan 1986), form follows failure (Petroski [1992] 1994), form follows material (Ashby & Johnson 2002), and form follows idea (Naylor & Ball 2005).

In computational design, form follows mathematics. Computational design is the use of explicit mathematical processes to describe and generate designs (McGill 2001); a computational model can be (or not) implemented in a digital environment. This approach is having an increasingly bigger impact on design research and practice (Oxman 2006). Computational design tools support the designer in the exploration and generation of a large variety of designs. These tools allow the generation of complex outcomes with simple rules.

Generative design systems can be applied in different design domains, such as urban design, architecture, product design, pattern design, fashion design, applied arts, animation, and engineering. **Fig. 1.5** illustrates applications in three different design domains (pattern design, product design and architectural design). Moreover, generative design tools can be applied in different phases of the design process (research, concept, development, detail, and production). They may also address different design tasks, such as representation, generation and evaluation. The form may be explored and generated through addition processes (e.g. additive shape grammars), subtractive processes (e.g. topology optimization) or transformation processes (e.g. parametric design). **Fig. 1.5** illustrates these three different approaches, respectively from left to right.

Fig. 1.5. Computational design applications in different domains; from left to right: Islamic patterns (Jowers et al. 2010), Bone chair – designed by Joris Laarman in 2006 (MoMA 2016), Sagrada Família window (Burry, Burry & Faulí 2001)

1.2 Research Problem

The individuals of a class reveal an apparent formal chaos. However, underneath the differences among them, there are similar characteristics which they all share. The study of the form through an ontological and mathematical approach provides a means to find the underlying rules that (de)codify that diversity. Within this motivation, this research intends to encode the formal diversity inherent to one product class, and to verify its applicability as a design tool for the concept phase of product design. The challenge is to find simple rules that can explain and generate a large variety of objects within one product class, in such a way that it can be useful for designers.

This research gives a particular emphasis to the previously described form A (structural form), in the search for a mathematical and abstract description of the structure of a product, and to the form D (ontological form), in the search for the essence of the form of a product, i.e., the properties shared by all the products of a class. The study of the formal diversity will be conducted through the case of multipurpose chairs. The variety of the class is illustrated in **Fig. 1.6**. In order to find simplicity behind the apparent complexity, there are two key questions that need to be answered:

1) *What makes a chair a chair*?

2) *What makes a chair unique*?

The answer to the first question addresses the basic elements common to all chairs (the seat and the backrest), and the answer to the second question addresses the large number of variations that can be found within the class (e.g. chairs with solid, opened, or mesh-shaped backrests).

The practical application of this study is translated into a generative design tool. The outcomes are intended to address two major problems found in the field of computational generative design: (1) generative design tools are limited in scope; and (2) generative design tools lack practical application (Chase 2005). The contributions of the tool to overcome these problems will be discussed in section **1.7**.

Fig. 1.6 *All the Chairs I Sat On* (Hancock 2008)

1.3 Research Goals

Main Goal

To develop a computational model capable of describing and generating a large number of design types within one product class, and to test its applicability as a design tool intended for the concept phase of the design process.

Secondary Goals

This thesis is divided into eight chapters. With the exception of the **Introduction** and the **Conclusion** chapters, each chapter addresses a specific secondary goal. The chapters and the corresponding goals are as follows:

1) **State of the Art**: to develop a theoretical framework concerning computational design, focusing the studies on form. Include a theoretical overview and a characterization of the main processes for the description and generation of forms, giving examples from the domain of chair design.

2) **Multipurpose Chair Sample**: to select a set of designs representative of the multipurpose chair class, including designs from several different types and from three particular styles.

3) **Multipurpose Chair Ontology**: to develop a computational ontology able to describe the form and the structure of the multipurpose chair class, based on literature review and on the analysis of the designs of the Multipurpose Chair Sample.

4) **Multipurpose Chair Grammar**: to develop a parametric set grammar based on the Multipurpose Chair Ontology, in order to allow the analysis and generation of a wide set of chair types, including the ones described in the Multipurpose Chair Sample.

5) **The ChairDNA Digital Tool**: to implement the Multipurpose Chair Grammar in a digital environment, in order to provide a useful and intuitive tool for designers in the concept phase of the design process.

6) **User Evaluation of ChairDNA**: to evaluate the practical applicability of ChairDNA as a tool for design students and practitioners in the concept phase of the multipurpose chair design process.

1.4 Research Questions

Main Research Question

1) Is a computational model, capable of describing and generating a large set of multipurpose chair types, a useful tool in the concept phase of the design process?

Secondary Research Questions

2) What methodology would be effective in the development of a model that allows a systematic description and generation of a large variety of designs within a product class?

3) What degree of completeness can be achieved with a computational model that intends to reproduce as many types of chairs as possible?

4) What is the practical applicability of a design tool that is able to generate several types of designs, to the concept phase of the product design process?

1.5 Hypothesis

A computational model capable of generating a large variety of multipurpose chair types is a useful tool in the concept phase of chair design.

1.6 Research Methodology

The research methodology comprised the development of a computational model (illustrated in **Fig. 1.7**) and its application to a case study, which refers to a particular product class. The overall goal of the model is to describe and generate designs within a product class. The model refers to the format and the case study to the content of the research. The model is based on a mixed methodology, comprising both quantitative and qualitative methods, which will be further described.

Research Model

The computational model is inspired in the spiral model for software development featured by Barry Boehm in 1986 (Boehm 1986, 1988). It is characterized by an iterative and incremental process of development lifecycle. The development of the model is made by n cycles (called **versions**) which go through the same sequence of n **stages**. The model evolves in increasing levels of complexity, detail, and completion along the versions. Every time a stage is revisited, the development is supported by the knowledge acquired in previous cycles. The model comprises six stages, each one addressing its own specific goals, methods and tools:

Stage 1) **Plan:** definition of the product subclass, goals and requirements for each version. The product subclasses of the various versions must be part of a single product class which the model is intended to describe and generate.

Stage 2) **Sample**: selection of a sample of designs representative of the product subclass. The sampling methods should consider the defined goals for the version; in this case the methods employed were judgment sample and theoretical sample (Marshall 1996). The characteristics of the designs are detailed in a database, stored in Microsoft Excel spreadsheets and summarised in datasheets.

Stage 3) **Ontology**: development of the analytic system, according to the computational ontology formalism (Gruber 1993). The ontology ensures a coherent taxonomic description of elements and their relations, within a domain. The development of the ontology included the methods of literature review and artefact analysis of the designs of the sample (Martin & Hanington 2012). The analytic model is represented by diagrams, developed in the software Visual Understanding Environment (Kumar & Kahle 2006), by descriptions, stored in Microsoft Excel spreadsheets, and by vector-based schemas.

Stage 4) **Grammar**: development of the generative system, following the shape grammars formalism (Stiny & Gips 1972). This approach allows the analysis and generation of designs through algorithmic shape rules, combining both mathematical and visual reasoning. In this case, the developed grammar is ontology-based (Beirão, Duarte & Stouffs 2009), is parametric (Stiny 1980), and is a set grammar (and thus it can be represented both graphically and symbolically). It was developed across the versions using a transformation method, i.e., by re-writing rules and parameters (Knight 1989).

Stage 5) **Implementation**: translation of the grammar into a digital environment, according to the method described in Garcia & Menezes Leitão (2018). The implementation allowed for the shape grammar to be tested and to release a tool which permits the quick and effective exploration of designs. The tool was programmed in Racket, using Rosetta to ensure the connection between the programming language and the CAD software (Lopes & Leitão 2011).

Stage 6) **Evaluation**: validation of the tool with potential users, which in this case comprised both design students and design practitioners. The user evaluation was conducted following the method of usability testing (Barnum 2011), including interviews and questionnaires (before and after testing), and observation and think-aloud protocol (during testing).

Case Study

The computational model was tested with the product class of multipurpose chairs. A multipurpose chair is a chair that can suit several uses. The choice of this product class is justified by three main reasons: firstly, the chair is one of the most important and studied objects in the history of product design, and became ubiquitous in contemporary Western societies. Chairs are a reflection of sociological, cultural and technological changes, and are frequently the most iconic objects created by renowned designers. Secondly, the chair product class comprises a large formal, material, symbolic, and structural variety. It can be composed by different articulated components or by a single piece, but its form is always restricted to the human body in a sitting position. Thirdly, multipurpose chairs can be structurally complex but maintain simple and functional forms, since they do not consider complex mechanisms, superfluous decoration and upholstery. This feature simplifies the analysis and gives emphasis to the structure of the object.

The development of the model comprised four main versions. The versions are characterized according to the subclasses of multipurpose chairs that the model incrementally analyses and generates:

Version 0.1) **Daciano Chairs**: multipurpose wooden frame chairs of the Portuguese designer Daciano da Costa;

Version 0.2) **Daciano-Jasper Chairs**: multipurpose wooden frame chairs of two designers: Daciano da Costa and the English designer Jasper Morrison;

Version 1.1) **Iconic Chairs**: multipurpose iconic chairs, including wooden frame chairs of the German company Thonet GmbH;

Version 1.2) **Multipurpose Chairs**: multipurpose chairs, including the subclasses of the previous versions.

The computational model is represented in **Fig. 1.7**. Both **Implementation** and **Evaluation** stages were not addressed in the first two versions (depicted in the figure in shaded grey). The development process started and stopped in the **Plan** stage. The last development step (**Plan** stage of the Version 2.1) comprised a requirements list for future iterations of the model. Each chapter of the thesis is dedicated to a particular stage of the model (excluding the **Introduction**, **Conclusion** and **State of the Art** chapters).

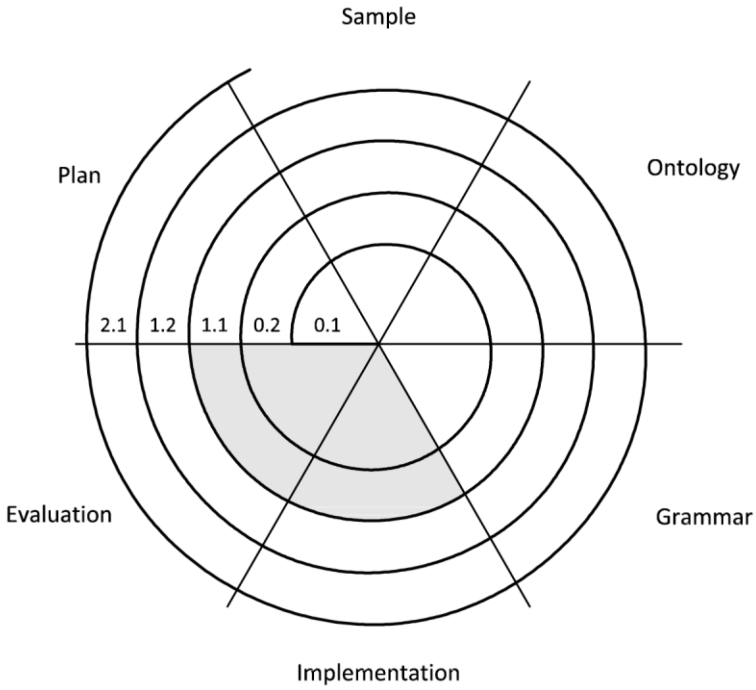

Fig. 1.7 Computational model

1.7 Significance

The major outcome of this research is translated into a design tool for the concept phase of multipurpose chair design. The tool is able to generate a wide diversity of design types (some of them unanticipated), while ensuring the necessary restrictions inherent to the class (the designs obey to correct anthropometric standards). With the tool, the user can generate designs by adding or deleting chair parts, and by manipulating their parameters, related to position, size, and shape. The interaction, made in a graphical user interface, has a real-time feedback in a 3D digital model, generated in a variety of CAD applications. The designs can be generated from scratch or from the redesign of predefined solutions.

This research also presents a methodology for the development of such tool. Starting from the analysis of a sample of designs and literature review, an analytic system (ontology) and a generative system (grammar) are developed. Both systems are based on two main kinds of representations: symbolic (the language of computation) and graphical (the language of design). The methodology also comprises the evaluation of the tool by target users (design students and design practitioners). The methodology can be generalized to the development of other tools.

The results of the evaluation with both novice and experienced chair designers revealed the usefulness of the tool in the generation and visualization of designs, quickly and accurately. The tool is potentially helpful in the exploration of the solution space, in redesign, and in overcoming creative blocks, since it is capable of producing surprising solutions. The usability of the tool was positively and negatively evaluated. On the one hand, the tool is easy to learn, but on the other hand, it lacks the intuitiveness and fluidness of the freehand drawing, as it is based on fragmented components of the chair. Note that it was not the tool's intention to mimic the designer's design process. Currently, the tool addresses the concept design phase. It generates incomplete and imperfect designs, since it relies mostly in the definition of the structure and it does not ensure constructive reliability. For future developments of the tool, the users highlighted the usefulness of having a higher degree of shape detail and to add materiality.

The major significance of this research addresses the two main problems mentioned in section **1.2**:

1) *Generative design tools are limited in scope* (Chase 2005). These tools comprise limited solution spaces, since they are often confined to a particular design style (as the case of analytic shape grammars) or to a particular design family (as the case of parametric models). This research constitutes a step to overcome this shortcoming, by presenting a methodology to develop a tool that describes and generates a wide diversity of design types within a product class.

2) *Generative design tools lack practical application* (Chase 2005). These tools are mostly used as a proof of concept with analytical or educational purposes. As a consequence, they are usually merely tested by the system developer or by students. Currently available design tools lack application in real-life design scenarios, particularly in early concept phases (McKay et al. 2012). Mostly they rely upon representation tasks and do not embody the knowledge of specific-domain generation tasks. This is the case of product design tools, but in graphic design domains there are already several available tools for generation tasks, such as web design and type design. This research contributes with a tool oriented for the concept phase of the product design practice. The tool was tested by design students and design practitioners.

1.8 Thesis Structure

This thesis is divided into eight chapters. The summary of each chapter is described below.

1. Introduction

This introductory chapter defines the concerns, approaches and methodologies employed in this research. The research background, the research problem, the research goals and the research questions are described. The hypothesis and the research methodology employed to test it are presented. The significance of the study is clarified. Finally, the structure of the thesis is specified through a brief summary of each chapter.

2. State of the Art

The state of the art describes the precedent studies within the scientific field of computational design, particularly the ones approaching the studies on form. A theoretical overview is provided, from a historical, technical and critical perspective. The major descriptive and generative methods and tools within computational design are described, being exemplified with some of the most recent applications in the chair design domain. A particular emphasis will be made in the shape grammar formalism and its applications. This theoretical framework, developed following the method of literature review, allowed the classification of the most relevant methods and the discussion of some key issues which supported the development of the computational model.

3. Multipurpose Chair Sample

The selection of a representative sample from a population provides feasible data for analysis and inference of other individuals within the population. This chapter comprises a characterization of Modern multipurpose chairs, selected as a case study for this research. This population was divided into four subpopulations: wooden frame chairs of a Portuguese designer, wooden frame chairs of an English designer, Western iconic chairs, and wooden chairs of a German manufacturing company. From these subpopulations, a sample of 46 multipurpose chairs was selected, based on judgment and theoretical sampling methods. A database that collects information about the chairs was developed, including details around design, production, commercialization, materials, techniques, dimensions and types.

4. Multipurpose Chair Ontology

An ontology is an effective means of capturing similar characteristics (shared by all individuals) and distinctive characteristics (specific to each individual) inherent to a product class. In this chapter, an ontological classification of multipurpose chairs is provided, with a particular emphasis in the parts of the chair and its types, in the generic shape and overall dimensions. Other features concerning product knowledge are also mentioned, such as functions (primary, practical, aesthetic and symbolic), materials and construction, as well as features concerning the generation process knowledge. The ontology was developed according to the methods of literature review and artefact analysis. The main features of the computational ontology are presented in a systematic way through schemas, descriptions and diagrams.

5. Multipurpose Chair Grammar

Shape grammars are rule-based formalisms that allow the description and generation of a large variety of designs. This chapter presents a parametric set grammar (a particular type of shape grammars) for the analysis and generation of multipurpose chairs. It will be shown how this generic grammar can be customized into three specific grammars, which describe and generate designs comprising three styles (of two well-known designers and one manufacturing company), one hybrid and one common grammar. The grammar was designed according to an analytic method, and is ontology-based. Moreover, as the grammar was being incrementally developed along four versions, the transformation method was also employed. The grammar was tested in terms of its descriptive, analytic and generative capabilities.

6. The ChairDNA Digital Tool

The implementation of design tools in digital environments allows its refinement and enhancement of generation efficiency and speed. In this chapter, the implementation of the Multipurpose Chair Grammar into the digital design tool ChairDNA is described. The tool is intended to provide a useful and intuitive aid for designers in the concept phase of the chair design process. The two major versions of ChairDNA (1.1 and 1.2) are discussed, as well as recommendations for future versions. The tool was developed according to a methodology for the implementation of set grammars into digital tools, through the translation of rules and parameters into user interface elements. A set of designs generated by the tool is presented, considering the descriptive, analytic and generative tests.

7. User Evaluation of ChairDNA

The evaluation of a product by its potential users is one of the most effective means of ensuring its usability and usefulness. The ChairDNA tool was evaluated by two distinct types of end users, with different levels of design expertise. A first evaluation was made to ChairDNA 1.1 by design students, and a second evaluation was made to ChairDNA 1.2 by design practitioners. For both evaluations, the main task was to design a multipurpose chair, using the tool. The usability tests included different methods, such as observation, think-aloud protocol, interviews and questionnaires. The participants successfully accomplished the task, and in general positively evaluated the tool as a valuable aid in the concept phase of chair design.

8. Conclusion

This chapter provides an overview of the research and summarizes the research findings, divided into main findings (addressing the hypothesis and research questions), and secondary findings. An overall discussion is provided, considering different interpretations, criticisms, strengths and weaknesses of the findings. Moreover, the contributions of the research are clarified and, finally, a set of recommendations for future work is presented.

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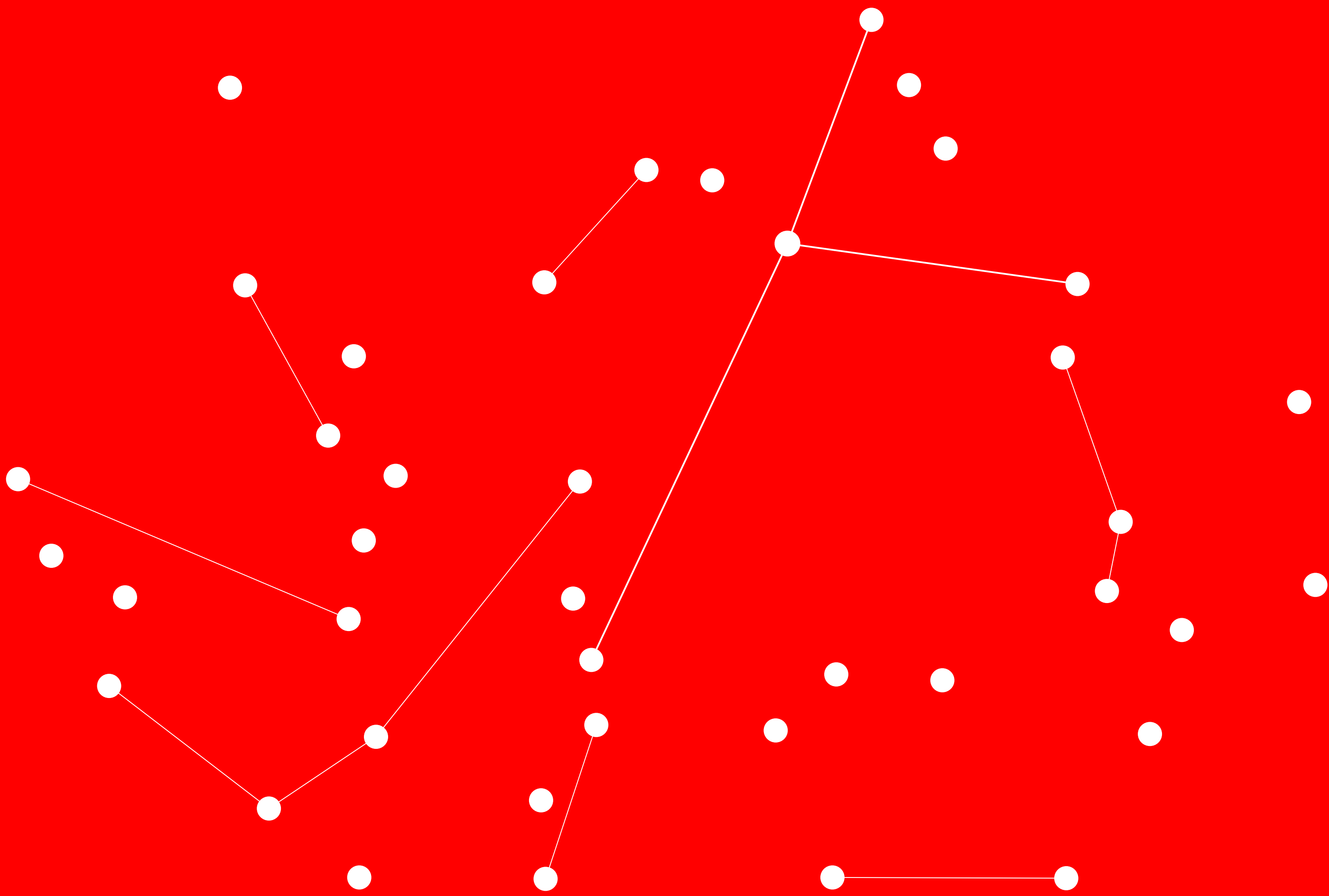

State of the Art

2

2 STATE OF THE ART

The state of the art describes the precedent studies within the scientific field of computational design, particularly the ones approaching the studies on form. A theoretical overview is provided, from a historical, technical and critical perspective. The major descriptive and generative methods and tools within computational design are described, being exemplified with some of the most recent applications in the chair design domain. A particular emphasis will be made in the shape grammar formalism and its applications. This theoretical framework, developed following the method of literature review, allowed the identification of the most relevant methods and the discussion of some key issues which supported the development of the computational model.

2.1 Introduction

This state of the art comprises the domain of computational design, which results from the symbiosis of two disciplines: design and computation. Design may be regarded as the process of solving a design problem, while computation is a mathematical and logical approach of addressing a problem. Some concepts concerning this research area are often used interchangeably:

1) *Computational Design*: "is an algorithmic system for the synthesis and analysis of designs" (McGill 2001, p.19). A computational design process can be or not implemented on a computer: "while computation is the procedure of calculating, i.e. determining something by mathematical or logical methods, computerization is the act of entering, processing, or storing information in a computer or computer system" (Terzidis 2006, p.57);

2) *Algorithmic Design*: "an algorithm is a process of addressing a problem in a finite number of steps" (Terzidis 2006, p.15). Algorithmic design is the use of algorithms in the process of solving a design problem. Algorithmic rules can be or not defined and executed on a computer. The usage of algorithms in design, for instance to generate or edit forms, is also called Algorithms-Aided Design (Tedeschi 2014). This definition may be considered equivalent to the one of *computational design*;

3) *Computer-Aided Design (CAD)*: is the use of computer programs to assist the designer throughout the design process. CAD tools are commonly associated with Computer-Aided Drafting, as being restricted to representation tasks (2D drawing and 3D modelling). However, although CAD systems always encompasses an interaction with a 2D or 3D formal representation (Oxman 2006), they can also address other design tasks (such as generation and evaluation). The CAD terminology can be extended to address more specific design domains (e.g. Computer-Aided Architectural Design and Com-

puter-Aided Industrial Design). Moreover, CAD is frequently integrated with Computer-Aided Engineering (CAE) and Computer-Aided Manufacturing (CAM), coordinating design with later phases of the product development. CAD focuses on shape definition, CAE on performance and optimization, and CAM on fabrication;

4) *Digital Design*: is a digitally mediated computational design (Oxman 2006). Digital design involves the "reduction of a process into discrete patterns and the articulation of these patterns into new entities to be used by a computer (…); digital is a process not a product" (Terzidis 2006, p.39). Digital design goes beyond CAD technologies; more than just a tool, digital design is a new process of design (Oxman 2006);

5) *Generative Design*: generative systems "can be operated to produce a variety of potential solutions" (Mitchell 1975, p.128). These computational systems can be applied in the generation of designs. Generative design focus on the process by which several designs are produced, comprising a shift on the designer's role: "instead of modeling an external form, designers articulate an internal generative logic, which then produces, in an automatic fashion, a range of possibilities from which the designer could choose an appropriate formal proposition for further development" (Kolarevic 2003, p.17). A generative design system contains a certain degree of autonomy in relation to its user; it can be: (i) a tool that is totally controlled by the user, (ii) a creative partner, or (iii) an autonomous creative entity (McCormack et al. 2014). Generative processes have been applied to other creative disciplines (such as art, music, and literature).

Based on the former definitions, the terms employed throughout this chapter are the following: (i) ***computational design***: the use of mathematical reasoning to address a design problem; (ii) ***digital design***: computer-implemented computational design; (iii) ***CAD***: digital design tools based on graphic representations (digital drawings or models); and (iv) ***generative design***: the use of computational processes to generate designs.

Computational design systems can be briefly classified as following:

1) *Medium*: the use (or not) of digital computers to process the computation. The duality of the media can be described though different terminology: physical environment *versus* digital environment (Oxman 2006), hand computation *versus* computer computation (McGill 2001), and analogue design *versus* digital design (Burry 2011). The terminology employed throughout this chapter will be physical *versus* digital.

2) *Design Domain*: the design discipline to which the computational system is applied, such as: urban design, architectural design, interior design, engineering design, product design, fashion design, graphic design, and so forth.

3) *Design Task:* the design task (or tasks) addressed by the computational system, such as: representation, generation, and evaluation. The design phase (research, concept, development, detail, and production) can also be referred.

4) *Automation Level:* the degree of autonomy of a computational system; from partially automated to completely automated. Mitchell (1975) defined five automation levels, considering three tasks (representation, generation and evaluation) and two types of problems (well-defined and ill-defined). The levels, from the lowest to the highest, are characterized by which tasks are performed by the machine: (i) representation (e.g. 2D digital drawing and 3D digital modelling); (ii) representation and evaluation (e.g. structural analysis); (iii) representation and generation (e.g. generation of all potential solutions of a problem); (iv) representation, evaluation and generation (e.g. optimization) – these first four levels address well-defined problems; and (v) representation, evaluation and generation within ill-defined problems. The levels are illustrated in **Table 2.1**.

Table 2.1 Automation levels (according to Mitchell 1975)

Problems	**Well-defined**			**Ill-defined**
Tasks	**Representation**	**Generation**	**Evaluation**	**All**
Low	Machine	Human	Human	Human
Medium Low	Machine	Human	Machine	Human
Medium	Machine	Machine	Human	Human
Medium High	Machine	Machine	Machine	Human
High	Machine	Machine	Machine	Machine

Legend

Human

Machine

In computational design, designers create a mathematical process that controls the generation of several objects, rather than just creating a single object. The process is as important as the final design. Therefore, some computational design processes and examples of resulting designs will be described in this chapter. Each illustrated design is a manifestation of multiple designs.

This state of the art is focused on systems which mathematically describe and generate the form of designs. A particular emphasis will be made on the formalism of shape and set grammars. Another focus relies on the applicability of such computational systems as digital design tools, whereby digital chair design will be particularly addressed.

This chapter is structured as follows: firstly, an overview of computational design is conducted, from a historical perspective and from the classification of different types of digital design tools. Secondly, a particular focus is given on generative computational systems, throughout the characterization of the main formalisms. The theory will be illustrated with examples within the chair design domain. Lastly, a critical overview discusses the intricate relation between design and computation. In the conclusion section, the theoretical positioning regarding this research is clarified.

2.2 An Overview of Computational Design

2.2.1 A Brief History of Computational Design

This brief historical overview of computational design is divided into two paradigmatic periods: (pre-digital) computational design and digital (computational) design.

Computational Design

The use of mathematical processes in design has been widely explored by architects since the ancient world. Architectural treatises, which describe systematic design rules, were developed in the 1st century BC (Vitruvius [1486] 2002)[1], in the Renaissance (Palladio [1570] 1965), and are still currently undertaken (Le Corbusier [1950] 2010). Rules of symmetry and proportion, as well as geometric shapes, were applied in the design of monuments, temples, palaces, and houses, from the classical era (e.g. the Parthenon in Greece) to the contemporary world (e.g. the Sydney Opera House). A wide variety of tessellations can be found in Islamic geometric patterns (e.g. in the tiles of the Alhambra palace in Spain), while some Indian temples exhibit fractal-like shapes (e.g. the Kandariya Mahadeva Temple in India).

The 1960s were a groundbreaking decade for the theory and practice of computational design. Renowned architects formalized mathematical strategies to generate designs: Peter Eisenman externalized a logical generation process based on syntactic operations, and Luigi Moretti employed the self-proclaimed parametric architecture approach in the generation of soccer stadium models. Frei Otto employed form-finding techniques, by using soap film models to explore intricate organic forms, which were applied for example in the Olympic Stadium of Munich. Otto was inspired on the hanging chain models of Antoni Gaudí, developed in the 19th century for the design of the catenary curves of the *Sagrada Família* temple in Barcelona.

Formal design methods, which were already taught in the Bauhaus design school (1919-1933), were oriented to a scientific approach to design in the Ulm School of Design (1953-1968). Under the leadership of Tomás Maldonado, the Ulm school promoted the integration of mathematical knowledge into design, by including quantitative problem solving methods such as statistics, probability theory, graph theory, symmetry and topology. Maldonado invited several specialists from scientific fields, such as the influential design theorist Horst Rittel, who developed innovative scientific design methodologies, for instance by relating the design process with cybernetics (involving feedback). Computational design thinking encompassed a symbiosis between symbolic and graphic representations in problem resolution (Neves & Rocha 2013).

[1] Although the treatise was written in the 1st century BC, the first printed edition of "De architectura" is dated from 1486, published in Italy by Giovanni Sulpitius da Veroli (Sanchez 1991).

The idea that the design process could be externalized and rationalized was proclaimed by a scientific approach to design, emerged during the 1960s. This approach described design as an activity of rational problem solving (Simon [1969] 1996). The design process was regarded as algorithmic and sequential (**Fig. 2.1**, left), starting from the problem (input), and ending on the solution (output). The design process would consist in searching for the best alternative within the solution space, which contained all the possible solutions for a given problem. The pioneer of this approach, Herbert Simon, was also one of the pioneers of the Artificial Intelligence (AI) research field, in an era where computers were starting to emerge. He believed that the design process could be codified, and thus the computer could compete or even replace the designers. This approach was followed by architects such as Christopher Alexander, who developed a mathematical system for the decomposition of design problems (Alexander 1964).

The first Conference on Design Methods, held in London in 1962, had three main goals: "(1) to design better, by understanding the design process, (2) to externalize the design process, allowing large teams to collaborate from the early stages and reaching a higher level of complexity, and (3) to use the computer to automate repetitive parts of the design process" (Celani & Veloso 2015, p.48).

However, the scientific approach to design was questioned in the 1970s, arguing that design was an activity of reflection in action (Schön 1983). The process delineated by Schön was later described as an hermeneutic approach, where problem and solution co-evolve throughout the process (Snodgrass & Coyne 1997). According to this approach, design is a cyclic process (**Fig. 2.1**, middle), where problem and solution are interdependent and are being completed and reinterpreted throughout the process. Inputs are gathered and outputs are generated during the process; outputs turn into inputs and *vice versa*. This design process can be also described as a parallel process, where problem and solution are developed at the same time, but while the problem space decreases the solution space increases (**Fig. 2.1**, right). This artistic approach defended that design problems could not be entirely codified, as they rely on ill-defined, incomplete and inaccurate information. It is worth mentioning that the co-evolution approach has been explored more recently by computational design processes (Maher & Poon 1996).

These two conflicting approaches to the design process can be summarized by regarding the designer as a scientist *versus* the designer as an artist. (i) The scientific process is external and rational, is guided by the use of knowledge in problem-solving activities, and deals with well-defined problems. (ii) In opposition, the artistic approach is internal and subjective, is guided by the use of experience, intuition and creativity, and considers ill-defined problems.

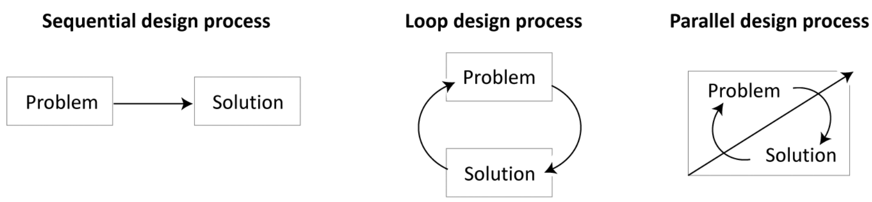

Fig. 2.1 Design processes: problem to solution (adapted from Dubberly 2004, p.27)

Digital Design

Algorithms have been utilised since antiquity, but the concept of a programmable general-purpose digital computer[2] was only developed in the 1930s (Turing 1936). One of the earliest digital computers, called ENIAC, was built in 1946. During the 1940s, computers manipulated alphanumeric information, and were mainly used to perform calculations within military and industrial applications. Computers only captured the interest of art and design domains with the advent of graphic computation in the 1950s. The introduction of cathode ray tubes allowed graphic images to be directly visualized on the computer screen.

The first interactive program of graphic computation, Sketchpad, was developed in 1963 by Ian Sutherland. The program is considered a landmark in the field of digital design. Sketchpad allowed the user to draw points, lines and arcs directly on the screen using a light pen; it included four views, some Euclidean transformations (scale, rotation and translation), and incorporated some parametric principles.

The first computers with graphical interfaces were developed in the early 1970s at the Xerox Palo Alto Research Center. Meanwhile, despite the advances made on graphic computation, computers were still sparsely used in design domains. This can be explained, on the one hand, by the fact that computers were still voluminous and expensive and, on the other hand, by some scepticism about the usefulness of computers in design domains. At the time, the computer was used as a drafting tool, with the goal of freeing the designer from repetitive, time-consuming tasks. The machine was mostly used to reproduce hand-made technical drawings, but, although it could execute repetitive tasks quickly and accurately, there was some apprehension from the designers regarding the loss of individual expression, freedom and creativity, and the alienation of forms and materials. The support of the representation shifted from the paper and pencil to the screen, mouse and keyboard, but it did not affect the design method.

> *"All the attempts at designing for new media have involved adopting pre-existing notions of visual narrative without closer consideration of the unique properties of the digital medium" (Maeda [1999] 2001, p.252).*

Meanwhile, during the 1970s, the combination of CAM and CAE techniques with CAD systems went through a major development. For instance, Computer Numerical Control (CNC) machines used digital drawings to regulate fabrication tools and machines, while CAE systems, comprising analysis and simulation capabilities, were being developed in automotive and aerospace industries. The computer allowed complex forms, which were complicated to design and expensive to produce, to be generated and fabricated. "It was a tool that should, in theory, allow architects greater freedom than ever before to create new structures and forms" (Bruegmann 1989, p.146).

[2] A digital computer is a programmable electronic machine that is capable of receiving inputs, of performing operations according to a set of instructions, and of producing outputs.

It was only in the 1980s that computers were massively spread in design domains. This boom was motivated by developments in hardware and software at the end of the 1970s and beginning of the 1980s. On the one hand, the development of the first personal computer in 1979 (called Apple II) turned computers cheaper and portable, while inkjet printers that were able to materialize digital images were introduced. On the other hand, computer graphics software comprised advances on 3D solid modelling, which allowed the production of hidden lines, shading effects and animations. One of the most currently widespread CAD software, AutoCAD, was launched in 1982 (although it did not include many of the advances introduced by Sketchpad). In the mid-1980s, new graphical capabilities emerged with the advent of pixel images, which allowed making realistic visualizations of digital objects, by simulating a great variety of colours and textures. At that time, despite all the advances and although CAD systems were accessible to everyone, they were still used to speed up repetitive drafting tasks.

The late 1980s and the 1990s brought further breakthroughs to the digital design field. The Pro/ENGINEER software (launched in 1987) introduced 3D parametric drawing for mechanical design. Moreover, designers attempted to go beyond the usage of software applications by programming their own routines (Tedeschi 2014). In the 1990s, the dissemination of internet and computer-aided technologies had a relevant impact on design processes. One of the most iconic and revolutionary digital projects, contemplating a total digital process from design to production (integrating CAD/CAE/CAM technologies), is the Guggenheim Museum Bilbao designed by Frank Gehry (inaugurated in 1997). In the mid-1990s, a new paradigm of production emerged with mass customization, allowing to produce one-off products without increasing the costs, integrating users in the design process and decentralizing the production (Bürdek 2005).

In the 21th century, research on digital design has been addressing several fields, such as the ones of generative design, virtual and augmented reality, artificial intelligence, quantum, biological and ubiquitous computing, and cybernetics and robotics. A brief overview on currently available digital design tools will be discussed in the next section.

2.2.2 Digital Design Tools

Design tools are devices intended to aid designers in the accomplishment of a given design task. Tools can comprise methods (such as drawing), objects (such as pencils and rulers), or software. Some typically used design tools include drawing (such as technical drawing, sketches and diagrams), modelling and brainstorming, among others. Drawing is probably the most traditional design tool, as a means of representation and design thinking.

Computational tools (such as the computer) support individuals in performing computations. Digital design tools are computational tools implemented in digital environments and applied in design domains. Currently, the most widespread digital design tool is CAD software. These tools are general-purpose and are traditionally focused on supporting digital drawing and modelling tasks. Meanwhile, digital tools can encompass more specialized design knowledge. For instance, ErgoCAD (Fernandez, Marley & Eyada 1990) is specialized on a design task (ergonomic evaluation), while BikeCAD (Curry 2017) addresses a specific product design (allowing to edit the shape and appearance of bicycles). A digital tool can also be designed to suit a particular design domain (e.g. web design) or a specific individual – since a user can add extra functions to an existing tool or program a custom design tool.

In the next sections, several types of digital design tools are discussed, regarding representation, generation, evaluation, fabrication, management, customization, and integrated tasks.

Representation Tools

The design process is based upon representations (Lawson 2004). Traditionally, the visual or graphic representations are considered predominant over the verbal ones. Representation tools can be used to visualize, develop, or communicate an idea. Nowadays, computers are commonly used for drawing, modelling, and animation tasks. As 2D drawing tools, computers speed up the production of technical drawings (for e.g. by automating repetitive tasks such as shading and copying) and allow flexible visualizations (for e.g. by displaying multiple views). However, their usefulness in producing freehand sketches is debatable, since a sketch is more fluid and inaccurate than the fragmented process of a CAD drawing (Lawson 2004).

Sketch Chair (**Fig. 2.2**) was 'sketched' directly in 3D space, with a pen whose movements were being recorded by motion capture technology, and transposed to a 3D digital model. The chair is printed in full-scale, using a 3D printer designed to manufacture car components.

Computers are also widely used for 3D digital modelling, comprising several advantages such as the automatic production of 2D drawings and photorealistic images. However, digital modelling is criticized for lacking intuitiveness, and for the misleading credibility of realistic images.

Name	**Sketch Chair (from Sketch Furniture collection)**
Design	Sofia Lagerkvist and Anna Lindgren (Front studio), 2005
Production	Alphaform
Materials	ABS-like resin
Techniques	3D Printing
Generation	Digital 3D sketching
Software	Motion capture software
Design Goal	Reduce time between the design idea and the production
Dimensions (mm)	W.485 x D.460 x H.765
Image Source	(V&A 2016)

Fig. 2.2 Chair designed by digital sketching processes

Generative Tools

Digital generation tools comprise computationally-based processes for the generation and transformation of form. Kolarevic (2003) called "digital morphogenesis" to the process of digitally exploring or finding form, which is shifting design from static to dynamic, from form-making to form-finding, and from single to multiple.

Digital tools allow for the description and generation of complex curvilinear forms, which would be highly impractical or even impossible to produce without computers, including non-

Euclidean and topological geometries. Moreover, form can be explored within performance constraints (e.g. morphological, material, economic, and environmental). Generative systems of formal production can be non-linear and indeterministic; because there is a complex network of interdependencies, a small change in its structure can dramatically change its behaviour. There are several generative processes, such as: combinatorial design, motion-based design, parametric design, rule-based design, grammar-based design, performance-based design and knowledge-based design. These processes will be described in detail in section **2.3.**

Generative design tools are relatively recent, and its adequacy and usefulness to the design process remains under debate. These tools have been criticized for being restricted in scope (e.g. comprising restricted design families) and for lacking practical application, since most of them do not go beyond the prototype phase (Chase 2005).

It has been argued that digital design tools lack application in concept phases of the design process (McKay et al. 2012). Nevertheless, digital design is gradually shifting its applicability, from a representation tool to a generation tool (Kolarevic 2003). “Computation is used today to analyze, simulate, and visualize real-world phenomena, and to design, invent, and explore new or imaginary phenomena” (Knight 2003, p.126).

Evaluation Tools

Digital evaluation tools can include various tasks: analysis (e.g. calculation of weight and centre of mass, and geometrical, structural, stress, thermal and environmental analysis), simulation (e.g. motion simulation, and simulation of assembly and production processes), evaluation (e.g. cost, ergonomics, and aesthetics evaluation) and optimization.

The R18 Ultra chair (**Fig. 2.3**) resulted from an optimization process. An interactive test collected data from several users; a pressure map analysis was employed, where built-in force sensors captured user’s loads and movements, observable in real-time on a colour simulation. The geometry and dimensions of the chair were optimized according to the collected data.

Name	**R18 Ultra chair**
Design	Clemens Weisshaar and Reem Kram, 2012
Production	Audi
Materials	Aluminium and carbon composites
Techniques	Folded sheet, robot welding
Generation	UNK
Software	UNK
Design Goal	Lightweight
Dimensions (mm)	W.404 x D.540 x H.785
Image Source	(Weisshaar, Kram & Audi 2017)

Fig. 2.3 Chair design applying digital analysis

Fabrication Tools

Digital fabrication involves the automated manufacturing of a product from a 3D digital model. This process can be used to fabricate prototypes (called rapid prototyping), moulds or end products. Digital processes allow the fabrication of forms that would be highly expensive to build with physical means. Moreover, they allowed the advent of mass customization, which enabled designers to be more directly involved with the manufacturing of their designs. CAM technologies, beyond controlling machine tools, are also used and to plan and manage the production. However, CAM machines still comprise limitations concerning the size and materials of the fabricated products.

The C2 Solid Chair (**Fig. 2.4**) was the first to be 3D-printed in one piece. New technologies bring new aesthetics, and digital fabrication is no exception. According to the designer Patrick Jounin, digital fabrication brings less technical constraints (when compared, for instance, to moulding techniques), and more freedom of forms. Furthermore, it shortens the time between the idea and the physical object, and allows the relocation of the fabrication. "It will definitely change how objects are thought and how they are produced in the future" (Jouin 2009).

Name	**C2 Solid Chair**
Design	Patrick Jouin, 2004
Production	Materialise NV
Materials	Epoxy resin
Techniques	Stereolithography
Generation	UNK
Software	UNK
Design Goal	3D-printing in one piece
Dimensions (mm)	W.404 x D.540 x H.785
Image Source	(MoMA 2016)

Fig. 2.4 Chair fabricated by digital processes

Management Tools

The design process comprises the creation and management of information. Moreover, it is a multidisciplinary team activity; the designer is a specialist in creative and communicative aspects, but is only a knower in ergonomics, engineering, and manufacturing (Bürdek 2005). The most widespread management digital tools include: (i) Product Lifecycle Management, which allows the management of information concerning design, production, transportation, sell, use and disposal, and (ii) Building Information Modelling, which associates a 3D model with all the information necessary for design, analysis, fabrication and assembly (including for e.g. production sequences, budgets, stocks, and bills of materials). An information model enables synthesizing, storing, coordinating and exchanging information related to all the phases of a product lifecycle. Meanwhile, computer networks can support collaborative work, allowing for remote design teams to interact.

Customization Tools

Digital customization tools are intended to help end users to configure their design ideas and obtain some performance feedback (such as the price of a given configuration). These tools do not require users to have special skills on design or computing, and they better suit the product to the user's needs. Some examples of customization tools are kitchen planners and product configurators. The Herman Miller product configurators (Herman Miller 2016) allow the user to customize online some components, materials, finishes, and colours. An example of a mass customized design is the Sinterchair (**Fig. 2.5**), being the basic structure of the chair configurable to unique customer's preferences (e.g. favourite music, books, and movies).

> *"Just imagine buying your furniture like made-to-measure suits (…) you receive a one-off product, tailored to your personal taste and requirements, that is ready for you to take home with you within 24 hours" (Byars 2006, p.156).*

Name	**Sinterchair**
Design	Oliver Vogt & Hermann Weizenegger, 2002
Production	UNK (prototype)
Materials	Nylon powder
Techniques	Selective Laser Sintering
Generation	The honeycomb structure is computer-generated, based on the user's preferences
Software	UNK
Design Goal	Mass customization
Dimensions (mm)	Variable
Image Source	(Byars 2006, p.157)

Fig. 2.5 Chair designed for mass customization

Integrated Tools

Digital integrated tools combine several tasks (such as representation, generation, evaluation and fabrication). An example of such tool is SketchChair (Saul et al. 2011), which integrates generation, analysis and fabrication capabilities. Within the tool, the user sketches the 2D profile of the chair and the software automatically generates the 3D model. Then, the user can perform stability and anthropometric tests, by resizing and repositioning a dummy on the 3D model. Lastly, the tool automatically produces the cutting profiles of the design, which can then be fabricated anywhere. SketchChair is currently available and is intended to be used by anyone (including end users), is able to share designs and can be also used as an education tool. The Antler chair (**Fig. 2.6**) is an example of a chair generated in the tool.

Name	**Antler Chair**
Design	Greg Saul (Diatom Studio) & JST ERATO Design UI Project, 2010
Production	UNK
Materials	Plywood
Techniques	CNC Milling
Generation	Digital 2D Sketching
Software	SketchChair
Design Goal	Design, analysis and manufacturing tool for end users
Dimensions (mm)	UNK
Image Source	(Saul & Rorke 2010)

Fig. 2.6 Design generated in SketchChair

2.3 Generative Design Systems

Computational generative systems can describe, analyse and/or generate form, according to formative (e.g. parametric modelling), additive (e.g. L-systems), or subtractive (e.g. optimization) strategies. The generative design systems described in this section are the following: combinatorial design, motion-based design, parametric design, rule-based design, grammar-based design, performance-based design, and knowledge-based design. Some systems will be illustrated with examples of computational generative design models applied to chair design, where one possible solution generated by each system is presented.

2.3.1 Combinatorial Design

Combinatorial design involves a systematic combination of design elements. Combinatorial techniques were used in the earliest generative systems (Mitchell 1975). In the 13th century, Ramon Lull developed a generative system which, by combining words and symbols inscribed in spinning concentric wheels, was expected to generate all possible knowledge. That idea was also expressed in the fable *The Library of Babel* (Borges [1944] 2013): all the books (those that have been written, those that will be written, and those that will never be written) can be created by the combinations of the same elements (letters and symbols). However, regarding the enormous amount of possibilities, the chance of finding a meaningful book is around zero. The exhaustive generation of possibilities can be useful if the set of possible solutions is limited and well-defined; otherwise, random or guided search procedures are usually employed.

Morphological analysis, a method developed by Fritz Zwicky in the 1960s, can be used for combinatorial design. For instance, the method was applied to the generation of office chairs (**Fig. 2.7**); by combining different shape configurations of five basic design elements, 108 different solutions can be produced (Hsiao & Chen 1997; Hsiao & Huang 2002). The shape of these basic elements was further detailed by a shape grammar (as it will be later described).

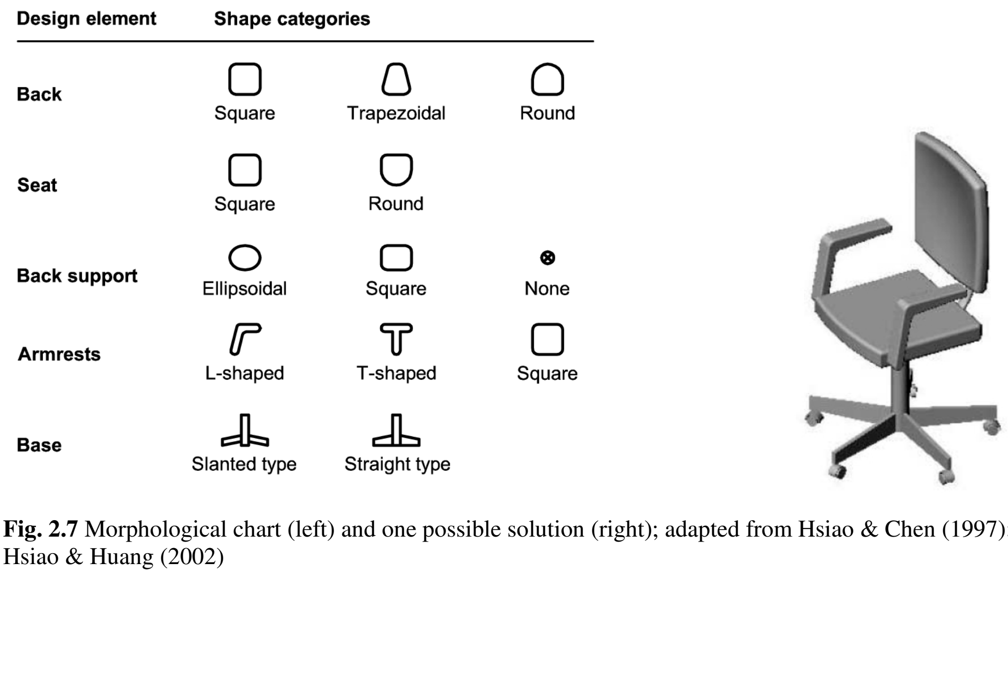

Fig. 2.7 Morphological chart (left) and one possible solution (right); adapted from Hsiao & Chen (1997); Hsiao & Huang (2002)

2.3.2 Motion-based Design

Motion-based design techniques use motion dynamics to operate transformations on forms (such as twisting and bending). Morphing is a motion-based technique to produce hybrids between two designs, combining their formal attributes. Rules of transition smoothly transform a base object into a target object (Terzidis 2006). One example of this process is the Eigenchair (**Fig. 2.8**, top), which is a hybrid between the **Wiggle** chair and the **Queen Anne** chair (both detailed in the chapter **Multipurpose Chair Sample**). The goal of the Eigenchair project (Roman 2013) was to create a 'genealogy' of chairs, containing information about existing chairs and the chairs that will be created in the future. The data-driven design process comprised the reduction of the 3D digital models of 12 iconic chairs into voxels (representing values on a 3D grid), and the generation of new designs by a morphing process between the values of two designs. Other example of the application of this technique to chair design is detailed by Sanchez et al. (2013), whose system was tested by an industrial designer.

Key-frame animation is another motion-based technique. It uses software to compute smooth interpolations between different states (key-frames). The process was employed in the generation of the CoReFab chair (**Fig. 2.8**, bottom). An animation process produces variations in a pattern (applied in a predefined generic form) according to certain parameters (Aldersey-Williams et al. 2008). One frame of the animation corresponds to a solution, such as the one illustrated in the figure. The project's ultimate goal was mass customization.

A third motion-based process is dynamics (Oxman 2006), where the form is a result of dynamic force fields. This idea was already explored by Thompson [1917] (1942). At the moment of formal conception, forms are transformed by influence of forces (such as gravity).

Name	**Eigenchair**
Design	Miro Roman, 2013
Production	UNK (scale model)
Materials	UNK
Techniques	3D Printing
Generation	Morphing
Software	Principal Component Analysis algorithm
Design Goal	Find the genealogy of chairs
Dimensions (mm)	UNK
Image Source	(Roman 2013)

Name	**CoReFab #116**
Design	Ammar Eloueini, 2006
Production	UNK
Materials	Polyamide nylon
Techniques	3D print
Generation	Stop-motion animation
Software	Autodesk Softimage
Design Goal	Mass customization
Dimensions (mm)	W.440 x D.520 x H.800
Image Source	(MoMA 2016)

Fig. 2.8 Chairs generated by motion-based design

2.3.3 Parametric Design

Parametric design (or parameter-based design) concerns the development of parametric models. A parametric model is able to generate a potentially infinite variety of topologically identical forms, i.e., "which remain invariant through continuous one-to-one transformations or elastic deformations" (Kolarevic 2003, p.18). The same topological structure can be manifested in an infinite number of different forms. For instance, a square and a rectangle are topologically identical but are dimensionally different. A parametric model (or a schema) is defined upon interrelated parameters (dependent or independent variables). A particular instance of the model (a fixed shape) is achieved when values are assigned to the variables of the model. The lattice deformations of Thompson [1917] (1942), which are illustrated in the **Introduction** chapter, can be regarded as an example of analogue parametric design.

Parametric modelling is useful for describing complex forms (such as Bézier curves or isomorphic surfaces), for generating design families, and for quickly editing forms. Moreover, parametric design can be combined with analysis and optimization techniques. Meanwhile, one challenge of designing parametrically is to setup and evaluate the range of possible outcomes (Kilian 2006).

Parameters may be related to different conditions, such as geometric, structural, aesthetical, economical, and environmental constraints. The form of a design is a product of different design constraints; they are usually interrelated, have different weights, some are contradictory and some are variable. Constrain modelling comprises making trade-offs between constraints. This process was employed on an experiment conducted by Kilian (2006), whose main goal was to overcome a current shortcoming of parametric models, which according to Kilian focus mainly on geometry parameters and neglect the integration of constraints such as material strength and assembly sequences. The design illustrated in **Fig. 2.9** is an outcome of a parametric model which comprises constraints related to material (thickness and curvature), fabrication (joints tolerance) and aesthetics (proportion and distribution and number of parts). The constraints are circularly dependent; i.e., the change of one parameter will affect all the others. The design goals comprised the use of plywood and to achieve a light appearance (similar to a rib).

Name	**Chair Experiment**
Design	Axel Kilian, 2006
Production	UNK (prototype)
Materials	Plywood
Techniques	CNC – Laser Cut
Generation	Constraint modelling
Software	CATIA, Generative Components
Design Goal	Explore circular dependencies in design problems
Dimensions (mm)	UNK
Image Source	(Kilian 2006, p.162)

Fig. 2.9 Chair generated by parametric design methods

2.3.4 Rule-based Design

Rule-based systems are production systems, which were originally defined by Post (1943). There are several types of production systems, but they all encompass the same underlying structure (Gips & Stiny 1980). These systems are based on production rules from the format $u \rightarrow v$ (i.e., if-then rules), where u and v are objects. The rule applies to an object w whenever u matches w under certain transformations. When the match is found, w is replaced by v under the same matching transformations. The generation starts from an initial object and proceeds by the recursive application of rules, until a final object is reached.

There are several types of objects. Originally in Post production systems (Post 1943), u and v are symbols. In shape grammars (Stiny & Gips 1972), u and v are labelled shapes (a combination of shapes with symbols). In pattern languages (Alexander et al. 1977), u and v are verbal descriptions; each rule describes a recurrent design problem and suggests an hypothetic abstract solution (if problem → then solution), being u the problem and v the solution. Discursive grammars (Duarte 2005) combine shapes, symbols and verbal descriptions. Some examples of rule-based systems are described below:

1) *Cellular Automata*: is a discrete model, originally developed in the 1940s by Stanislaw Ulam and John Neumann. The model is composed by a grid of cells. Rules describe the growth of the cells, changing the state of each cell in relation to its neighbour cells. One of the most well-known examples of cellular automata is the 'Game of Life', developed by John Conway in 1970;

2) *L-systems*: are recursive rule systems, developed in the 1960s (Lindenmayer 1968) to describe the plants growth. The system uses $u \rightarrow v$ rewriting rules, where u and v are strings. A simple set of rules can generate very complex objects after a few iterations;

3) *Iterated Function Systems*: are a method for the production of fractal shapes, introduced in the 1980s (Hutchinson 1981).

The term *fractal* was coined by Mandelbrot in the 1970s (Mandelbrot [1977] 1983). Fractals are self-similar patterns, generated by a mathematical recursive process. These patterns are often used to describe the roughness, openness, and branchiness qualities of natural forms (such as clouds, trees, and mountains), and have also been explored in artistic experiments with mathematics. **Fig. 2.10** shows the generation process of the Koch snowflake fractal, including one rule and a derivation. The rule illustrated on the left is in a shape grammar format. However, the rule can also be described by the L-systems formalism as following: F → F+F--F+F (where "F" means draw forward, "+" means rotate 60°, and "-" means rotate -60°).

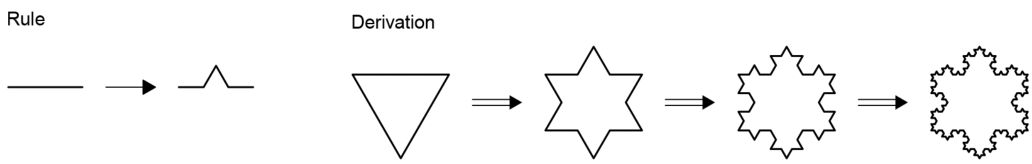

Fig. 2.10 Rule-based generation of the Koch snowflake

2.3.5 Grammar-based Design

Grammar-based design or grammatical design comprises rule-based systems, which generate objects within a language and using a given vocabulary. Formal grammars were firstly defined by Chomsky [1957] (2002). Chomsky developed a generative linguistic grammar to create grammatically correct sentences, composed by strings of symbols. Unlike string grammars, which operate with one-dimensional objects, spatial grammars are formal grammars that deal with objects in 2D or 3D spaces (Krishnamurti & Stouffs 1993). Spatial grammars may operate directly on spatial objects (shape grammars) or on representations of those objects, using strings of symbols (string grammars), finite sets of entities (set grammars), or graphs (graph grammars).

Shape Grammars and Set Grammars

Shape Grammars (SGs), a formalism defined in the early 1970s (Stiny & Gips 1972), are grammar-based systems for the description and generation of designs (Stiny 1980a). An SG is essentially defined by an initial shape and by if-then shape rules, from the type Left-Hand Side (LHS) → Right-Hand Side (RHS). The rules are applied to an initial shape, step-by-step, until the final solution is reached.

A shape is a "finite but possibly empty set of basic elements that are maximal with respect to one another" (Stiny 1992, p.413). The RHS can be an empty shape, unlike the initial shape and LHS (Stiny 1980a). Shapes are defined by basic elements (points, lines, planes and solids), which can be rectilinear or curvilinear, and usually operate in a 2D or 3D space. Shapes can have associated qualities, such as weights (Stiny 1992) and descriptions (Stiny 1981). SGs embody emergence, i.e., the ability to recognize and use emergent shapes, which are given by the decomposition of shapes (subshapes). Emergent shapes are not predefined by the grammar vocabulary; they emerge during the computation.

Set grammars are a restriction of SGs, since they do not contemplate emergent shapes. Therefore, while SGs combine and divide shapes, set grammars only combine shapes. SGs operate directly on shapes, while set grammars operate on symbolic representations of shapes. The lack of emergence reduces ambiguity, which may be considered a benefit or a weakness. On the one hand, set grammars are more amenable for digital implementation (Stiny 1982), considering criteria of efficiency (since the avoidance of subshape matching limits uncontrolled combinatorial explosion), utility (since emergent shapes may not be useful), and usability (since the selection of one solution among a large number of alternatives may become an unproductive task). On the other hand, set grammars reduce the range of unpredictable solutions and, presumably, creativity (Knight 2003). Still, both shape and set grammars are as powerful as Turing machines (Gips 1975).

In the following lines, a brief classification of SGs is provided, considering different methods, purposes, implementations, and applications. The classification is extensible to set grammars. A more detailed SG classification and glossary were developed along this research (Garcia 2016).

Methods

SGs can be developed according to three main methods: analytic, synthetic, and transformation (Knight 1999a). In (i) analytic SGs (Stiny & Mitchell 1978), rules are developed from the analysis of a corpus of existing designs from an given language. The language can characterize a design style, a product brand, a design collection, a product class, and so forth. Within the same style, the corpus can contain designs from one type (Stiny & Mitchell 1978), or several different types (Flemming 1987). Analytic SGs can describe a corpus of designs, analyse other existing designs, and generate new designs within the language. In (ii) synthetic SGs (Stiny 1980b), rules are developed from a vocabulary of shapes, using a constructive method. Synthetic SGs can generate new designs within an original language of designs. (iii) Transformation SGs (Knight 1989) combine analytic and synthetic methods. Rules are developed from the transformation of rules of a given grammar, through rule addition, deletion and change. Transformation SGs may generate existing languages or new languages of designs.

SGs can be extended, creating a more generic SG, or restricted, creating a more specific SG. A grammar can be extended by the addition of rules and/or parameters, extension of parametric ranges, or the deletion of labels, and can be restricted using opposite strategies. Generic SGs (Li 2001), also known as general SGs, can be customized to specific SGs, which characterize a sublanguage of the generic SG language. SGs can comprise different levels of *genericness* (Castro e Costa & Duarte 2014); for instance, an SG which characterizes a design family is less generic than an SG which characterizes context-independent design patterns (Beirão, Duarte & Stouffs 2011). The selection of the level of *genericness* is a key feature for the grammar development: "if the rules are too specific to a problem, then the system is limited to certain range of designs. If the rules are too general, then the system does not have the specific kind of knowledge for the users to benefit from" (Lee & Tang 2004, p.12).

SGs can be combined with other techniques, for instance: (i) *parametric SGs* (Stiny 1980a) consider parametric shapes (schemas) instead of shapes; (ii) *shape annealing* is a method that combines SGs with the simulated annealing optimization technique (Shea & Cagan 1999), (iii) *evolutionary SGs* combine evolutionary algorithms with SGs (Ang et al. 2006); (iv) and *ontology-based SG*s combine formal ontologies with SGs (Beirão, Duarte & Stouffs 2011).

Purposes

SGs can consider a variety of different purposes. For instance, they may be used as (i) design tools, (ii) analysis tools, (iii) customization tools, and (iv) educational tools. Each tool comprises a main target user (designers, historians, end users, and students, respectively).

(i) As design tools, SGs have been applied to the generation of art and design objects. They can be based on synthetic SGs (generating designs within an original language) or on analytic SGs (generating designs within an existing language), since both the generation of new design styles and the reuse of existing design styles are significant strategies of design innovation (Ahmad & Chase 2012). SGs may provide different design strategies for their users (Knight 1999b): (i) additive (comprising the addition of parts); (ii) subdivision (comprising the subdivision of a boundary), and (iii) grid (comprising the addition of parts within an underlying grid). Some SG developers intend the rules to mimic a natural and intuitive design process, such as the artisan fabrication process (Stiny 1977). In other cases, the grammar strategy may not mimic any existing process, but still providing a valuable generation method.

As design devices, SGs comprise some identified advantages and disadvantages. (i) On the positive side, Knight (2003) argues that emergence in SGs promotes four key features of the design process: interaction, novelty, unpredictability and ambiguity. Moreover, it is argued that the outcomes of an SG have a considerable aesthetic value, since they combine structural simplicity and visual complexity (Stiny & Gips 1972). SGs are also useful to externalize and share design knowledge, generate design families, and easily transform designs and processes. (ii) On the negative side, and despite some developers defend that SGs can generate unexpected, creative solutions (Orsborn et al. 2006), others defend that solutions are not truly innovative since they are implicit in the grammar (Kirsch & Kirsch 1986). Moreover, design grammars comprise less ambiguity than abstract grammars (since they assign meanings to shapes). SGs also comprise inference problems – from a finite corpus of designs it is not possible to infer all the designs of a potentially infinite language (Stiny 1980b), and efficiency problems – SGs can produce undesirable results (which do not meet the design goals). This latter problem may be overcome by the use of goal-oriented search techniques, either automated or performed by the user (Knight 1999b). Another current shortcoming of design SGs is that they are usually tested only by the grammar developer and by students. In fact, most of the applications of SGs as design tools are in early research phases and do not have a real impact in practice.

(ii) As analysis tools, SGs are usually based on analytic SGs. These grammars can be useful to identify design styles, identify inspirations or influences, recreate designs, classify designs, and so forth. However, the definition of style by analytic SGs comprises some shortcomings: (i) an SG may generate designs that do not belong to the style; (ii) an SG may not be able to generate all the designs from the style; and (iii) an SG may incompletely define the style (Ahmad & Chase 2012). Moreover, in most cases, the style evaluation is only made by the grammar developer; some exceptional examples include the evaluation of an architectural style by its author and one collaborator (Duarte 2001) and the evaluation of the key features of a product brand by its consumers (Pugliese & Cagan 2002).

(iii) As customization tools, SGs can be applied as product configurators, and oriented for mass customization. Some examples comprise the customization of housing (Duarte 2001), Thonet chairs (Barros, Duarte & Chaparro 2011) and ceramic tableware (Castro e Costa & Duarte 2014). The first example comprised the evaluation of original designs by one end user, one architect, one engineer and graduate students (Duarte 2001). The third example considered two target users: the designer (which sets a design family), and the end user (which sets one solution).

(iv) As educational tools, SGs can teach design students about design languages, formal design processes, methods for externalizing the design process, and design families. Early SGs examples comprised pedagogical purposes (Stiny 1980b). Some educational SGs were tested by design students (e.g., Li 2001).

Implementation

An SG can be implemented in a digital environment. The implementation can be made on an SG interpreter, which allows the user to develop an SG; compiles an SG (i.e., calculates the applicability of rules); and allows the user to use an SG, i.e., to apply of the rules and generate new designs (Tapia 1999). An SG interpreter should also provide an intuitive user interface, display editable shapes graphically, and address different variants in shapes, including parametric/non-parametric, 2D/3D, rectilinear/curvilinear, surfaces/solids, weights and descriptions, and emergent shapes (Li et al. 2009; Chau et al. 2004). SG interpreters started to be developed along the early developments of SGs (Gips 1975), being one of the most well-known examples the GEdit (Tapia 1999) interpreter, which supports emergency. Some examples of currently available SG interpreters are the following: 3D Shaper (Wang & Duarte 2002), Shaper 2D (McGill & Knight 2004), Grammar Environment (Li et al. 2009), SGI (Trescak, Rodriguez & Esteva 2009), and GRAPE (Grasl & Economou 2013). Each interpreter is focused on exploring different features of SGs. A second option to implement SGs is as specific implementations, which only allow the user to use an SG, such as the example of the Ice-ray grammar implementation (Liew 2001).

Application Domain

SGs have been applied in visual domains, such as urban design (e.g. Beirão, Duarte & Stouffs 2011), architectural design (e.g. Stiny & Mitchell 1978), interior design (e.g. Eloy & Duarte 2012), product design (e.g. Agarwal & Cagan 1998), engineering design (e.g. Shea & Cagan 1999), pattern design (e.g. Stiny 1977), and graphic design (e.g. Carlson, Woodbury & McKelvey 1991). The following lines will focus on SG applications in product design.

Table 2.2 summarizes a comparison of 15 product design grammars, regarding the following categories: (i) *Product class*: five grammars are applied to transportation design (addressing engineering design knowledge), three are applied to kitchenware design, and three to furniture design (including two grammars closer to the applied arts domain, since they address chair-back design). (ii) *Language*: most grammars address product classes (e.g., coffeemakers and motorcycles), two comprise brand identities (Coca-Cola and Buick), and two define design styles (Hepplewhite and Thonet). Some grammars only address object parts. (iii) *Sub-language*: four grammars include a more specific grammar: the coffeemaker grammar can be particularized to four brands (although restrictions are not detailed); the motorcycle grammar includes the Harley-Davidson grammar (specifying rule and parameter restrictions); the cross-over vehicle grammar is customizable to three existing vehicle subclasses, one existing hybrid class and a new vehicle subclass; and the tableware grammar can generate six different design collections of a given manufacturing company. (iv) *Rule number*: the grammars comprise a different number of rules, from 4 to 100. (v) *Shape*: most grammar rules employ a 2D representation of the shape; which are often converted to a 3D shape at the end of the process (e.g. coffeemaker and tableware grammars). Most grammars use lines and arcs or ellipses to describe the shape, and some make a conversion to more complex curves at the end of the computation (e.g. Hepplewhite and Thonet grammars). (v) *Parametric*: almost all the grammars are parametric.

Table 2.2 Comparison of product design grammars

Product Class	Language	Sub-language	Rule No.	Shape	Parametric	Reference
Furniture (chairs)	Hepplewhite chairs (back)	N/A	7	2D lines	Yes	(Knight 1980)
	Office chairs	N/A	UNK	UNK	UNK	(Hsiao & Chen 1997)
	Thonet chairs (back)	N/A	34	2D lines	Yes	(Barros, Duarte & Chaparro 2011)
Kitchenware	Coffeemakers	Krups, et al.	100	2D lines & ellipses	Yes	(Agarwal & Cagan 1998)
	Kettles	N/A	UNK	2D curves	Yes	(Prats et al. 2006)
	Tableware	Company	UNK	2D Bézier curves	Yes	(Castro e Costa & Duarte 2014)
Transportation	Motorcycles	Harley-Davidson	45	2D lines & ellipses	Yes	(Pugliese & Cagan 2002)
	Inner-hood panels	N/A	24	2D lines	Yes	(McCormack & Cagan 2002)
	Buick vehicles (front view)	N/A	63	2D Bézier curves	Yes	(McCormack & Cagan 2004)
	Bicycle frames	N/A	4	2D lines & arcs	Yes	(Suppapitnarm et al. 2004)
	Cross-over vehicles	Coupes, Pick-ups, SUVs	70	2D Bézier curves	Yes	(Orsborn et al. 2006)
Packaging (bottles)	Coca-Cola bottles	N/A	12	2D lines & arcs	Yes	(Chau et al. 2004)
	Bottles	N/A	14	3D lines & ellipses	Yes	(Chen et al. 2004)
Healthcare	Ultrasound transducers	N/A	39	2D & 3D arcs	Yes	(Culbertson 2012)
Consumer electronics	Digital cameras	N/A	46	2D arcs	No	(Lee & Tang 2004)

Other comparative studies of product design grammars reveal that the most used design strategy is the additive (Barros 2015), as in the motorcycle grammar, although the subdivision strategy is also employed, as in the Thonet grammar. Products are often decomposed into functional parts (Ang et al. 2006), as the example of the coffeemaker, motorcycle, and tableware grammars. The shape of the designs may be represented by the contour (e.g. tableware grammar), the inner structure (e.g. Thonet grammar), or the solid region (e.g. bottle grammar).

Product design grammars are often combined with other techniques: (i) *generation*: the office chair grammar combines SGs with morphological analysis (as previously described). (ii) *Evaluation*: the coffeemaker grammar contemplates cost evaluation (Agarwal, Cagan & Constantine 1999), and the office chair grammar includes a semantic evaluation. (iii) *Optimization*: the Thonet grammar combines SGs with parametric design and optimization techniques (some resulting designs are illustrated in **Fig. 2.11**), and the bicycle frame grammar use multi-objective shape annealing. (iv) *Evolutionary design*: the digital camera grammar and the Coca-Cola bottle grammar (Ang et al. 2006) were combined with genetic algorithms.

Some grammars were implemented in digital environments, namely, the Coca-Cola bottle grammar was implemented in the SGS interpreter, and the Thonet grammar was implemented as a set of parametric models.

Name	**Designs generated by the Thonet chair grammar**
Design	Mário Barros, 2011
Production	*Laboratório de Prototipagem Rápida*, FAUL (scale models)
Materials	Gypsum powder
Techniques	3D Print by ZCorp
Generation	Shape grammars and parametric modelling
Software	CATIA
Design Goal	Mass customization
Dimensions (mm)	Variable
Image Source	(Barros, Duarte & Chaparro 2011)

Fig. 2.11 Chair generated by grammar-based design methods

2.3.6 Performance-based Design

Performance-based design (or performative design) is a broad concept, addressing systems that use performance criteria to generate, evaluate and select designs, employing iterative processes. The performance criteria can be related to technical, financial, ecological, aesthetical, and ergonomic constraints, among others. Currently, performance-based design can be decomposed into two main fields: design optimization and evolutionary design.

Design optimization: optimization algorithms search for the best solution within several alternatives, considering single or multiple objective functions and a set of constraints. These functions (or design goals) can be, for instance, to minimize the surface area (shape optimization), minimize the mass taking into account the material (topology optimization), or to strength the structure (structural optimization). Structural optimization was already employed with physical models (such as the handing chain models and the soap film models, previously mentioned). Optimization systems can use several techniques; for instance, the simulated annealing metaheuristic technique, which searches for a good solution (sacrificing the optimal solution) in a fixed period of time, comprising random selections.

Evolutionary design: evolutionary algorithms (such as genetic algorithms) combine optimization and evolutionary principles. Genetic algorithms are inspired on the process of natural selection, which is based on the survival of the fittest. A genetic algorithm generates several candidate solutions, evaluates solutions based on an objective function (fitness criteria), and applies crossover and mutation operations on some selected solutions in order to generate other candidate solutions. The process is repeated several times until a certain number of generations or a certain fitness level is achieved. The resulting solutions are often unexpected and thus apparently creative (Kolarevic 2003); however, it has been claimed that it is difficult to set up genetic algorithms and that there is little user intervention during the generation process (Kilian 2006).

Three examples of chairs generated by performance-based design techniques are illustrated in **Fig. 2.13**. The Bone chair (**Fig. 2.13**, above) was generated using a topology optimization process: from predefined seat and back surfaces and three support points on the floor, the algorithm gradually removes material from a solid volume, over which the loads of a sitting person are simulated (**Fig. 2.12**). The process is inspired by the capacity of the human bone to modulate itself and change its structure depending on the type of load (Aldersey-Williams et al. 2008). The Bone chair is one of the few examples of product designs generated by generative procedures that reached mass production.

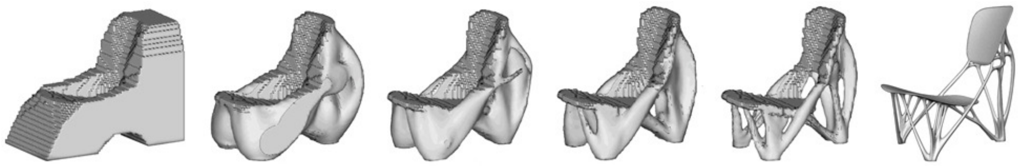

Fig. 2.12 Generation process of the Bone chair (Laarman 2006)

Unlike the previous example, where the initial form was a block, the Elbo chair (**Fig. 2.13**, middle) was generated from a 3D model of a design inspired by the Elbow Chair (by Hans Wegner) and the Lambda Chair (by Berkeley Mills). The optimization was undertaken with the Dreamcatcher generative design tool, by simulating the loads of a sitter on the seat and back surfaces. The final design performs better than the original, comprising 18% less material. Note that the chair exhibits a formal resemblance with bones, like the former example.

The Beast Chaise Longue (**Fig. 2.13**, below) represents a breakthrough over the previous examples, since the employed generative process changes not only the geometry but also the material. The design is constituted by a single continuous surface to which is applied a Voronoi cellular pattern. The form and the material adapt to structural, environmental and corporeal performance: the thickness is adapted to the load (the higher the load, the stiffer the material); the pattern size and density is adapted to the degree of curvature (the higher the curvature, the smaller the cells), and the flexibility is adapted to the skin-pressured areas, given by pressure map analysis (the higher the pressure, the softer and flexible the material).

Name	**Bone Chair**
Design	Joris Laarman, 2006
Production	Droog Design
Materials	Aluminium
Techniques	3D Printing (ceramic mould), moulding
Generation	Topology optimization
Software	Software from Opel
Design Goal	Maximum efficiency with minimum material
Dimensions (mm)	W.445 x D.759 x H.756
Image Source	(MoMA 2016)

Name	**Elbo Chair**
Design	Arthur Harsuvanakit and Brittany Presten, Autodesk, 2016
Production	Autodesk
Materials	Black walnut wood
Techniques	CNC milling
Generation	Optimization
Software	Dreamcatcher of Autodesk
Design Goal	Decrease volume and weight
Dimensions (mm)	UNK
Image Source	(Autodesk 2016)

Name	**Beast Chaise Lounge**
Design	Neri Oxman, 2008
Production	Stratasys (scale model)
Materials	Photopolymers
Techniques	Multi-material 3D printing
Generation	Structural, environmental and corporeal performance
Software	UNK
Design Goal	Exploration of material properties
Dimensions (mm)	UNK
Image Source	(Oxman 2010)

Fig. 2.13 Chairs generated by performance-based design methods

2.3.7 Knowledge-based Design

Knowledge-based design is a broad term, used to refer systems that use explicit knowledge bases for problem solving. A knowledge-based system is divided into a knowledge base (which represents facts about the world) and an inference engine (which makes assumptions about the world). Knowledge-based systems have been explored within the AI field; the early examples were known as expert systems, which captured and used specific-purpose knowledge of human experts to solve problems.

Computational Ontology

Computational ontologies were formalized in the 1990s as explicit and sharable representations of knowledge (Gruber 1993). Ontology-based systems are entity-relationship models, representing classes, relations and properties. Formal ontologies are incomplete, expandable, and comprise different abstraction levels. An example of a simple ontology applied to the chair design domain was described by Eastman (1992), where concepts concerning chair knowledge, their relations, and physical and functional properties are represented by a diagrammatic data model.

Machine Learning

Machine learning is the ability of computers to learn from experience, solving problems without being explicitly programmed. The field flourished in the 1990s, and has been mostly employed on object recognition and classification tasks, which were applied in several areas including the chair domain (e.g., Woods et al. 1995). In a very simple example, the system learns how to recognize a chair by analysing a set of 2D images or 3D models that were labelled as ‘chairs’ or as ‘non-chairs’.

Neural networks are learning algorithms, inspired in the mental processes of the human brain. Neural networks are constituted by connected units (neurons), which transmit signals (synapses) between each other. A neuron receives an input from its predecessor neuron, changes its internal state (activation), and produces an output to its successor neuron. Neutral networks have fault tolerance and learning, inductive, and parallel handling abilities. They are used, for instance, to find patterns in data. In the already mentioned computational system for office chair design (Hsiao & Huang 2002), a neural network was used for establishing relationships between adjectives and form parameters (embedded in a system developed through morphological analysis and SGs techniques). The system, intended for the design concept phase, allows the user to generate designs by regulating form parameters and getting feedback over the qualities of the designed product. However, despite the potential of the machine learning research field, its applicability in design tasks remains largely unexplored.

2.4 Computational Design Criticism

This section describes some critical viewpoints around computational design. The main focus of discussion is based on an underlying competition between humans and machines. Therefore, this critical overview is structured on the three main approaches to AI: (i) *strong AI* concerns the ability of the machine in exhibiting human-like intelligence in general tasks; (ii) *weak AI* concerns the ability of the machine in exhibiting human-like intelligence in specific tasks; and (iii) *synthetic AI* concerns the ability of the machine in exhibiting its own kind of intelligence.

(i) The question of whether computers can mimic or surpass the human intellect is one of the most debatable ones. Currently, machines are not able of reaching human intelligence, but the possibility of doing so in the future is not consensual. Some scientists believe that computers will become intelligent and aware of their own existence (Hawking et al. 2014), while others believe that it will never be possible, since computers will always struggle with basic tasks such as small talks (Searle 2014). It is relevant to acknowledge that the question “Can machines think?” is not equivalent to the question “Can machines exhibit intelligent behaviour?”. In the Turing test, a machine is considered to exhibit an intelligent behaviour if its conversation cannot be distinguished from a human's (Turing 1950). However, the fact that the machine is capable of simulating human language does not mean that it can actually understand language (Searle 1980).

(ii) Computers show ‘intelligence’ in specialized fields. Computers can play board games, pilot spacecrafts, and perform delicate surgeries. In 1997, the IBM's Deep Blue was the first computer to win a chess match against a chess world champion, and in 2015, the Google’s AlphaGo was the first computer program to defeat a professional human Go player, by learning how to play almost by itself, incrementally avoiding its errors. The Pepper humanoid robot, launched in 2014 by Software Robotics, has the ability to read emotions, while Sofia, developed by Hanson Robotics and activated in 2015, can show facial emotions, and “she” became the first robot to receive citizenship (in 2017).

(iii) In the synthetic AI approach, it is not intended to imitate human intelligence, since intelligence does not have a standard definition in the first place. Moreover, it is argued that the machine does not need to mimic human behaviour to achieve results regarded as intelligent. For instance, the way the computer plays chess games is very different from the human way; the computer uses rational processes while humans use intuition and experience.

> *"The question of whether Machines Can Think (…) is about as relevant as the question of whether Submarines Can Swim." (Dijkstra 1984)*

The question of whether machines can design is closely related to the one of whether machines can think (Cross 2001). Therefore, the three main AI approaches can be applied to the following three questions: (i) “Can Computers Design?”; (ii) “Are Computers Useful Design Partners?”; and (iii) “Can Computers Design in their Own Way?”. In the following lines, these three questions will be discussed, as well as a fourth one: “What is the Impact of Computers in Design?”.

Can Computers Design?

In section **2.2.1**, two opposite perspectives regarding the question “Is design computational?” were discussed. (i) The rationalistic approach of the 1960s (Newell & Simon 1963), based on AI theories, defended that the design process could be codified. It regarded design as a well-defined problem solving activity, based on the manipulation of symbols. The rationalistic vision separated the objective world of physical reality (made up of context-independent facts) from the subjective world of individual's mind (made up of mental symbolic representations of facts). (ii) The critics of the rationalist approach defended that the design process could not be codified. They regarded design as an activity of reflection in action, a cyclic co-evolutive process, ill-defined, inaccurate, and intuitive. Design, and human reasoning in general, was seen as based on experience, unconscious instincts and intuitions, which could not be formalized by symbolic representations (Dreyfus [1972] 1992). Dreyfus argued that in everyday situations, humans intuitively jump to the solution, based on their background and context, rather than employing a step-by-step logical process. Moreover, object and subject cannot be separated, since one cannot exist without the other; therefore, computer programs encompass a blindness problem, since they are always hypotheses that result from the developer’s interpretation (Winograd & Flores [1986] 1997). It has been argued that computers cannot design, since they cannot handle holistic design solutions and unconscious cognitive tasks (Lawson 2004). However, it is relevant to acknowledge that computers nowadays go beyond symbolic representations, concerning sub-symbolic approaches, dealing with incomplete information, anomalies, and making quick ‘judgments’.

Currently, computers are not suitable as autonomous designers. But will machines capable of designing in the future? Some authors believe that the computer will be able to design as well or even better than humans, while others (the majority) do not.

The first position would change the paradigm from the designer being aided by the computer to the computer being aided by the designer or, ultimately, to the computer being an autonomous designer. That position is defended by the architect Nicolas Negroponte, who dedicated a book “to the first machine that can appreciate the gesture” (Negroponte 1970). The lack of intervention of the designer is regarded as an advantage by Negroponte, since the computer-designer would guide the customer in selecting the best alternative according to its needs, without taking into consideration the designer’s personal tastes, beliefs and prejudices.

The second position is taken by several designers for whom the design depends on intuitiveness, talent, and intent, features that lack in machines. For them, computation objectifies what is subjective. Even though the technical side of design can be externalized, many things remain internalized, inside the designer’s mind (Kolarevic 2003). The machine can defeat chess masters, but it turned out to be much more difficult to program the making of design:

> *“Although it is clearly demonstrated that computers can solve certain types of problems (...), they cannot display anything corresponding to the original creative thought which is taken to be characteristic of a good designer.” (Mitchell 1975, p.146)*

> *"As a designer, I would like to believe that such goal [computer systems that can design autonomously] is impossible. There is nothing that prevents the encoding of a designer's basic intelligence in a digital form, but I subscribe to the belief that design is intuition, not intelligence. It is talent, not facts and rules. And if we can't teach humans how to be talented designers (…) I sincerely doubt that we can teach machines". (Maeda [1999] 2001, p.13)*

In auto-generative design systems, the designer at most configures only a few parameters and halts the process. Ostwald (2010) presented three ethic flaws of these systems: (i) *authorship*: since the designer does not have an active or visible role in the process, this would raise the question of who is the author of the design and who is responsible for it – the man or the machine?; (ii) *comportment*: the designer does not have the care to clearly explain the process; and (iii) *motivation*: the designer emphasizes a false complex scientific process, when often it was a simple process that produced complex forms, being the complexity solved by the authors of the algorithms. However, even in auto-generative design systems, the designer is responsible for the creative intent; even when computational forms go beyond control, it is still the designer that is affecting their change (Maeda [1999] 2001).

Creativity is a key feature of design. Therefore, the question "Are Computers Creative?" is discussed in the following lines. Creativity requires the generation of novel and valuable ideas, which may relate to solutions or processes (Sternberg 2006). There are two types of creative processes (McCormack et al. 2014): combinatorial creativity (where new elements arise from the combination of existing ones), and emergent creativity (where new elements arise *ex nihilo*). It was already discussed in this chapter that the computer can generate designs from combinations of existing ones and generate new emergent solutions.

Nevertheless, the question "Are computers creative?" can be replaced by the question "Are computers capable of generating creative solutions?". There are two positions regarding the answer. (i) On the one hand, Lady Lovelace argued that computers can only do what they are told, and thus are unable to create original solutions. Computers can merely produce apparently unanticipated results (such as random numbers), and are unable to generate creative solutions alone, as argued by John Maeda; without human inspiration, the computer only generates standard designs. (ii) On the other hand, it is argued that computers are capable of generating unpredictable and novel solutions, which are not anticipated by the algorithm developers (Terzidis 2006; Kolarevic 2003), and they are able to learn new creative processes. A machine can produce results that it was not programmed to do (thus is passes the Lovelace test for artificial creativity). However, like the critics of the Turing test, the fact that the computer is able to generate solutions or processes that are regarded as being creative, it does not mean that the computer is creative, since the machine does not have consciousness or creative intent.

Are Computers Useful Design Partners?

Design is increasingly being transferred to digital environments. Although computers are commonly not regarded as good autonomous designers, there seems to be no doubt that they provide useful design tools:

> *"Can the computer substitute for the Designer? Probably, in some special cases, but usually the computer is an aid to the Designer" (Eames 1972)*

Maeda [1999] (2001) foresees a synergy between designer and computer, where the designer's creativity is combined with the computer's speed and precision. Numbers are a design medium, comparable to sculpting clay or mixing paints. Terzidis (2006) is from the same opinion, suggesting that, given the complexity, uncertainty and ambiguity of design problems, a complementary relationship between the human and the machine would be beneficial.

Meanwhile, not all design tasks benefit from the computer support. Typically, the computer performs faster than human designers at well-defined tasks (e.g. information management tasks), while the designers perform better than computers at ill-defined tasks (e.g. creative and aesthetic evaluation tasks). A synergy between human and computer would combine the calculation speed, efficiency and accuracy of the computer and the human's capacity to deal with incomplete, incorrect and contradictory data. Some authors argue that most design tasks are ill-defined and thus not computable, while others claim the that most design tasks are well-defined (Flemming 1994). Two studies outlined below demonstrate the success of the computer in performing some design tasks:

(i) The first study regarded the usage of SGs as stand-alone design systems for the refurbishment of apartments (Eloy, Vermaas & Andrade n.d.). An evaluation similar to the Turing test was employed. A panel of ten architects assessed the design quality of two groups of designs: (i) grammar designs (generated by the SG developer using the default parameters), and (ii) architect's designs (generated by six human architects, which did not belong to the panel). It was told to the panel that all designs were generated by human architects. The results showed that the majority of the grammar designs were evaluated as having a higher quality than the architect's designs. Regardless, the authors of the study claim that only some design tasks are useful to be computable: repetitive tasks (since for singular tasks the human designer imprints more creativity and economy) or tasks where the design knowledge is time-consuming to collect.

(ii) The second study regarded a structural design problem (Shea & Cagan 1999). It compared roof truss designs generated by human designers (engineers and architects) to the ones generated by a computational system (using a shape annealing process). The results demonstrated that the computer was able to generate innovative designs, which were proven to be efficient and were considered visually expressive. Moreover, they contemplated unconventional configurations (such as asymmetric designs). For the authors, a structural design tool would be useful in providing new unforeseen possibilities that would tickle the designer's creativity and imagination.

Can Computers Design in their Own Way?

The argument that the computer needs to employ similar processes to the ones of human designers to achieve valid results is arguable. It was already discussed that the designer's process is guided by beliefs, intuition, and experience, using ill-defined processes such as metaphors and analogies, while the computer's process traditionally employs rational reasoning. Although design is not considered a rational and methodical activity (Terzidis 2006), the computer can provide an useful aid in those terms. Flemming (1994) argues that computers should perform differently from humans, in an environment where people and machines collaborate by performing different tasks. Negroponte (1970) enumerated three ways of how the computer could assist the designer: automate current procedures, change current procedures to make them computable, or both man and machine working together using their own procedures.

What is the Impact of Computers in Design?

The digital age brought a technological and cultural revolution, which also affected design. Nowadays, computers are widely used in several design activities, from education to practice. Digital design tools provide a useful aid in representation, generation, evaluation, fabrication and management tasks. Since the 1980s, when the computer achieved a widespread use in design practice, that both products and processes have changed.

> *"It has become clear that the computer, like any tool, inevitably changes, for better or for worse, the processes that it was meant to aid." (Bruegmann 1989, p.151)*

Some positive and negative impacts of computers in design tasks are summarized below:

1) *Representation*: design shifts from physical to digital. The virtual world is an intermediate reality between the imagination and the physical reality, between ideas and matter (Manzini 1992). Digital representation improved the speed and accuracy of repetitive design tasks and eased the visualization and communication of designs. However, because the differences between the physical and the digital world seem to be decreasing, the illusion that digital models are materialized end products may arise;

2) *Generation*: design shifts from static to dynamic, and a single product shifts to multiple products. There is a freedom of complex organic forms that can be designed, edited, and fabricated. Moreover, the designer's role shifts, from designers of products to designers of systems. Currently, there is still a separation between tool-makers and tool-users (Terzidis 2006); being the designers only users of digital tools. However, Maeda believes that the designer tends to combine both design and programming skills (for instance, one of the authors of SketchChair, Greg Saul, is both a designer and a programmer.). For that purpose, he created a programming language (Maeda [1999] 2001) for "visual people" (artists and designers), which would not require programming skills. Therefore, the designer would create and edit a generative system and interpret its output (Kolarevic 2003). Meanwhile, generative systems bring the danger of transferring the authorship and the responsibility of the design to the computer;

3) *Evaluation*: the introduction of analysis and optimization in earlier phases of the design process allows an earlier detection of problems, the reduction of physical prototypes and the reduction of costs and time inherent to the adaptation of an idea to the production. Analysis and simulation become accessible to the designer (since results are graphically displayed), which allows him/her to have a higher control and understanding over the technical restrictions. However, there may be an illusion that the designer can control the whole process, without requiring the expertise of other specialists;

4) *Fabrication*: the new paradigm of mass customization allows an affordable fabrication of a one-off design and the customization of products by the end user (choosing features such as colours, materials, sizes, and shapes), who ends up in having a higher intervention in the design. The proliferation of 3D printers allows products to be manufactured anywhere, reducing the need for storage and distribution. Lastly, digital fabrication (re)approximates design to production, thinking to making;

5) *Management*: the digital age has shortened the space-time notion. Information is more standardized, interconnected, accessible, and sharable. This reduces information loss and duplicated and contradictory information. The design process becomes more interactive and collaborative; the stakeholders (designers, engineers, manufacturers, marketers, clients, customers, etc.) can work together at the same time from different geographical locations. Ultimately, this will increment quality and productivity, save time and resources. However, it can become difficult to select relevant information, and the lack of face-to-face communication can also bring some shortcomings.

Currently, the use of the computer in design activities is still mostly restricted to representation tasks (Terzidis 2006). Computers are usually used in later phases of the design process, after an idea is established. Computers are not regarded as suitable tools for the concept phase, arguably because there is a higher degree of uncertainty (when compared to later design phases), because the language of the computer prevents designers from thinking creatively (Lawson 2004), or because computers are still regarded suspiciously:

> *"The use of algorithms to address formal problems is regarded suspiciously by some as an attempt to overlook human identity and creativity and give credit instead to an anonymous, mechanistic, and automated procedure." (Terzidis 2006, p.57)*

In conclusion, designers do not truly take advantage of the potential of the computer, in a way to revolutionize the design practice. And even if computers someday become great designers, this does not mean they would replace human designers; in the same way that the fact that machines play chess better than humans does not prevent humans from playing chess.

2.5 Conclusion and Research Outlook

The state of the art discussed in this chapter handled the symbiosis between two disciplines: design and computation. A brief historical overview of computational design, including a summary of the currently available digital tools, was provided. A particular emphasis was made in generative design tools, comprising the description of the most relevant formalisms for describing and generating the form (with a focus on grammar-based systems). The state of the art was illustrated with examples in digital chair design. Lastly, a critical discussion on the role of computers in design was undertaken.

Currently widespread digital tools for product design, such as CAD software, lack application in concept phases of the design process, and are mainly general-purpose, disregarding knowledge inherent to domain-specific design tasks. One sparse example of a design tool oriented for a particular product class is **SketchChair**. The tool allows end users to sketch the outline of a chair and automatically generates the profiles needed for laser cutting. However, the sketching process does not include anthropometric constraints; therefore, there is no guarantee that the result is a comfortable chair, or even a chair.

Generative design tools lack practical application, since they are mostly used for proof of concept in academic environments, and they are often limited in scope, addressing restricted design solutions and design properties. There are some generative design tools for chair design. (i) Hsiao & Chen (1997) proposed a method for developing a design tool for the concept phase, including the creation of a semantic model (with adjectives describing characteristics of a product) and the development of a grammar; the model was applied to the case of office chairs. (ii) Barros, Duarte & Chaparro (2015) proposed a model for developing a customization tool to support the entire design process, including the creation of a grammar, the implementation of some designs as parametric models, and the accomplishment of structural optimization; the model was applied to the case of Thonet chairs. Although these tools are directed to support the design process, they are not currently available and comprise restrictions in scope, since the solution space contains a small variety of design types.

The generative design domain holds great potential, but is still currently underdeveloped and has little practical application. On the one hand, most tools described in this chapter are currently unavailable, although the description of the computational process is frequently detailed. On the other hand, the majority of the designs produced by generative design processes, described in this chapter, are scale models (e.g. **Beast Chaise Lounge**), prototypes (e.g. **Sinterchair**) or are closer to art objects rather than design objects (e.g. **Eigenchair**).

Within the context of this state of the art, the theoretical positioning of this research will be outlined in the following lines, considering the formalisms, methods and approaches employed in the computational model detailed in the subsequent chapters.

The computational model will be based on the shape grammars formalism, since they are powerful devices, are based on visual reasoning, and can be combined with other techniques. The computational model will address four types of SGs: (i) set grammars (a more restricted type of SGs, which does not consider emergent shapes); (ii) parametric grammars (a grammar which contains parametric models); (iii) analytic grammars (developed from the analysis of a corpus of designs); and (iv) generic grammars (ontology-based systems that can be customized to specific grammars). Ontology-based systems have the advantage of providing clear, coherent, and detailed descriptions in the most consensual way.

The model is intended to be applied as a design tool for the concept phase. The tool's main goal is to provide a useful aid to the designer; it is neither intended to mimic the designer's process nor to replace the designer. The adopted approach regards the design process as a symbiosis between designers and machines, taking advantage of each one's strongest skills: the designer's creativity and intuition and the computer's speed and accuracy. It is argued that the design process benefits from cooperation rather than competition between designers and machines.

Given that, currently, generative design tools are merely evaluated by the tool developers or by students, the usefulness of the tool and its usability will be evaluated by design practitioners and design students. The computational model was developed upon the spiral model, which combines features of the waterfall model (sequential, parallel and with feedback loops), agile model (iterative and incremental) and prototype model. Feedback from end users was gathered in intermediate states of the model (and not from the beginning as in the user-centred design model), since the first goal was to generate as many types of designs as possible.

Computational generative systems are focused on particular design aspects, dealing with very few aspects of the design process. Meanwhile, generative tools must comprise trade-offs between restrictions (in order to produce valid results) and variations (in order to produce several different results). The tool developed in this research comprises an effort in extending the design domain, by contemplating several multipurpose chair types. Moreover, different design strategies are considered (therefore providing several possible generation sequences).

However, the tool remains restricted in several aspects: (i) design domain (multipurpose chairs); (ii) design phase (concept phase); (iii) product features (shape and structure); and (iv) design strategy (additive and transformation). Meanwhile, the tool comprises anthropometric restrictions, which ensure that the dimensions of the generated designs are suitable to multipurpose chairs. However, the tool does not prevent the final solution from being an invalid chair (since the tool can generate chairs that are uncomfortable and/or unstable). Nevertheless, regarding that the tool is intended to the design concept phase, some inaccuracy and imperfection can be considered advantageous.

This research is expected to contribute to the ongoing development of the generative design domain. Design is on the verge of a revolution; more than just a tool, computational generative design will become a new paradigm in design practice.

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Multipurpose Chair Sample

3

3 MULTIPURPOSE CHAIR SAMPLE

The selection of a representative sample of a population provides feasible data for analysis and inference of other individuals within the population. This chapter comprises a characterization of Modern multipurpose chairs, selected as a case study for the present research. This population was divided into four subpopulations: wooden frame chairs of a Portuguese designer, wooden frame chairs of an English designer, Western iconic chairs, and wooden chairs of a German manufacturing company. From these subpopulations, a sample of 46 multipurpose chairs was selected, based on judgment and theoretical sampling methods. A database collects information about the chairs of the sample, including details around design, production, commercialization, materials, techniques, dimensions and types.

3.1 Introduction

The present chapter refers to the second stage of the computational model specified in the **Introduction** chapter. The computational model was applied to a population of a specific product class, as a case study. The population is characterized by multipurpose chairs, designed in the Modern period (from the mid-19th century to the present), and bilaterally symmetric. The choice was mainly justified by the overall structural diversity and formal simplicity inherent to the class. Moreover, it is one of the most important and well-documented objects in product design history. The population is characterized by the following domain decomposition:

1) *Furniture*: objects whose function is to support human daily activities, such as sitting, eating, working, sleeping and storing. Furniture can be used furnish buildings (domestic, offices, hospitals) or urban spaces. Although usually movable, furniture can also be built-in.

2) *Seats*: furniture objects whose function is to support the human body in a sitting position (e.g. chairs, stools, sofas, and car seats).

3) *Chairs*: type of seat containing a backrest, for individual usage and movable. This product class present a large diversity of forms, structures, and materials.

4) *Multipurpose chairs*: type of chair that is suitable for several purposes, spaces, uses, and situations. This class excludes chairs for specific uses (e.g. office chairs and lounge chairs), for specific users (e.g. children's chairs), and chairs with mechanisms (e.g. folding chairs, recliner chairs, swivel chairs, and rolling chairs).

5) *Modern chairs*: chairs designed in the period between 1850 and the present. The chair is one of the most designed and studied objects in Modern era. The history of chair parallels the history of product design (Fiell & Fiell [1997] 2012), reflecting economics, technologies, and trends of the society in which it is designed. Modern chairs pre-

sent simple and functional forms, resulting of mass production processes, the rationality of the objects and the honesty of materials and construction. These chairs comprise minimum decoration, thus excluding elements with exclusively aesthetic, sculptural or pictorial purposes (e.g. carved wood). Moreover, only chairs with minimum upholstery were considered, in order to simplify the structural analysis (since there is a small amount of hidden parts).

6) *Symmetrical chairs*: only chairs with bilateral symmetry were selected, in order to simplify the generation process (since only half of the chair needs to be encoded). This restriction only excludes a small percentage of the chairs of the population, as the majority is symmetrical.

From the aforementioned population, four subpopulations were defined, comprising the different goals addressed in the four versions of the computational model. Two subpopulations are characterized by wooden frame chairs of two well-known designers. One addresses different types of Western iconic chairs, and other is defined by chairs of a renowned manufacturing company. For internal reference, each subpopulation is identified with an ID code (represented in brackets):

1) *Daciano da Costa* [**D**]: multipurpose wooden frame chairs designed by the Portuguese designer Daciano da Costa. This group is characterized by an individual style; its selection considered a regional criterion (Portuguese design) and the recognized quality, well-documentation and simplicity of the designs;

2) *Jasper Morrison* [**J**]: multipurpose wooden frame chairs designed by the English designer Jasper Morrison. This group is characterized by an individual style; as the former group, the selection criteria considered the recognized quality, well-documentation and simplicity of the designs, as well as a differentiation criterion (a designer from a different country and generation);

3) *Iconic* [**I**]: multipurpose Western iconic chairs from different types. This group is representative of the diversity of the class (since it considers technology breakthroughs), have recognized quality (since chairs are disclosed in museums or compendia, and many are commercially successful) and comprise accessible and updated documentation (since the majority is currently industrially produced). This subpopulation includes Portuguese Iconic chairs [**IP**] and Iconic stools [**IS**];

4) *Thonet* [**T**]: multipurpose wooden frame chairs currently manufactured by the company Thonet GmbH. This group was selected from a corpus of designs of a generative system (Barros, Duarte & Chaparro 2011).

The definition of these subpopulations comprised two sampling methods: (1) judgment sample (applied in subpopulations **D**, **J**, and **T**), where the selection considered the most effective sample to answer to the research question, based on the researcher's knowledge and available literature, and (2) theoretical sampling (applied in subpopulation **I**), where an iterative process between the elaboration of the theory and the sample was employed (Marshall 1996).

Each subpopulation has a corresponding database, comprising not only multipurpose chairs but all types of seats. The databases are available from **Appendix 3.A.1** to **Appendix 3.A.5**, containing a catalogue of seats organized alphabetically (by designer) and chronologically (by design date), and indicating the type of seat, the producer and the sampling source.

Fig. 3.1 illustrates the set diagram of the population domain decomposition (white background sets) and the four subpopulations (grey background sets). Two of the subpopulation sets overlap, because there are two sample individuals common to two subpopulations. Some categories refer to types (common nouns with an initial lower letter), while others refer to styles (proper nouns with an initial capital letter). Types are context-independent, while styles are context-dependent (to a person, period or place).

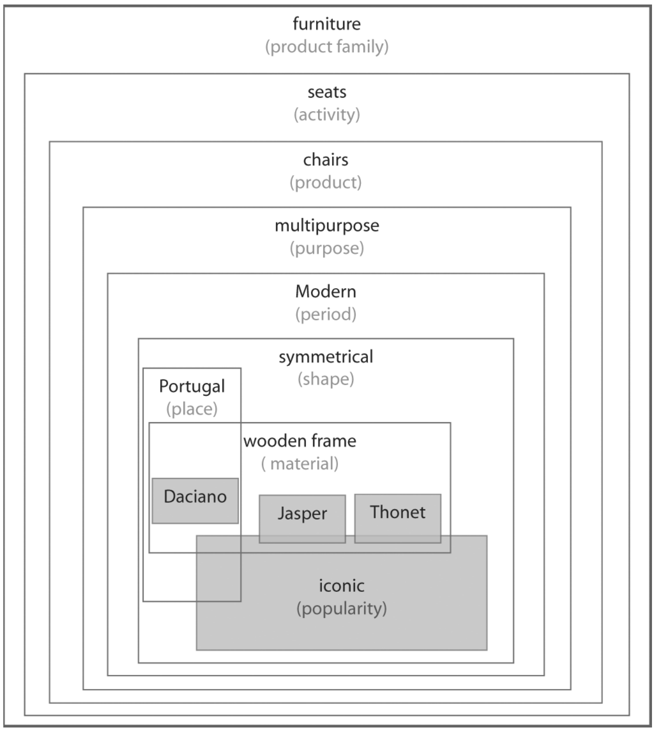

Fig. 3.1 Diagram of the population (white background sets) and subpopulations (grey background sets)

Each subpopulation is further subdivided into two main groups, according to the role within the construction of the computational model: Corpus designs [**C**] and Existing designs [**E**]. The first group constituted the main source for developing the system and the second group represented the control group. This will be further explained in the chapter **Multipurpose Chair Grammar**.

A sample containing 46 chairs and 1 stool was selected from the subpopulations. The sample individuals were designed between 1859 and 2011 in several countries across Western Europe and North America. The chairs of the sample are detailed in a database, available in **Appendix 3.B.1**, and illustrated in plates displayed in **Appendix 3.B.2**. The sample details will be summarized in this chapter in the format of datasheets, comprising the following information:

1) *ID*: internal ID codes, containing the aforementioned subpopulation codes.
2) *Name*: chair name, given by the most recent producer (except in Eames chairs, where the original name was used). The model of the chair is specified in the database. The selected model is either the most recent one (currently in production or not) or the one that has been in production for the longest time (when the chair has currently more than one producer).
3) *Design*: name of the designer and design date (of the original version). Details concerning the designer's nationality and birth and death dates are available in the database.
4) *Production*: name of the producer and production date. Note that the producer may not be the original one, and may not have the current exclusivity of the production (e.g. the Eames chairs are produced by Herman Miller in USA and by Vitra in Europe). In the case of the sample chairs, the producer is also the manufacturer (but may not manufacture the entire product). The company details (headquarters location and the date of foundation and defunct), the production type, and the other production companies can be consulted in the database.
5) *Commercialization*: name of the seller, which is either the producer or the official distributer (e.g. the exclusive distributer of Magis in USA is Herman Miller). The mentioned price is the one available in the seller online shop (updated in November 2016).
6) *Materials*: generic materials of the frame and support panels. In the database, the colour of the selected model is also specified.
7) *Techniques*: forming and cutting techniques of the frame and support panels. The techniques do not include early transformations of the raw material (e.g. the extrusion technique to produce tubular steel). In the database, the joining and finishing technologies are also specified.
8) *Dimensions*: displayed in millimetres (mm) by the following order: overall Width (W), Depth (D), Height (H), and Seat Height (SH). The measures were taken from three sources: the manufacturer's website (if the chairs are currently in production), the museum's website, or from author's measurements.
9) *Sampling criteria*: choice justification and sampling source.
10) *Image source*: the source of the displayed image of the chair.

The database contains additional information concerning the client and the context for which the product was designed, extra functions (stacking and indoor/outdoor use), type of chair, recyclability (percentage of recycled and recyclable materials), packaging (quantity, weight, dimensions and whether the product is disassembled), documents available in the manufacturers website (3D model and 2D drawings), patents, related products (collection, options, and variants[1]), design details (influences, goals and styles), and location (in museums and private collections).

This chapter is organized in two main sections: firstly, a brief historic characterization of the population is provided, and secondly, each subpopulation is described and the details of each sample unit are presented in datasheets. The sample individuals are grouped by the subpopulations, being the chairs of each group chronologically ordered (by the design date).

[1] The classification of the related products is inspired in the one of Nunes (2012): (1) *Collection* (also called product family, product series, line, or range) is a set of matching products intended to be used together, with different functions but with a similar style (e.g. the Tulip furniture collection includes a chair, a stool, and dining tables). Product variants can be obtained by changing some dimensions (e.g. DCW dinning chair and LCW lounge chair) and/or editing components (e.g. Tulip chair and armchair). (2) *Family* (also called versions or variants) comprise a set of products that share a similar function but have slight different appearances. Usually the options are customizable by the user, and consider variations in colour, material (e.g. chair 214 with woven cane seat and 214 M with plywood seat), finishing (e.g. 214 in veneered or stained), interchangeable parts (e.g. chair 214 with leather-back and 215 with solid-back), or additional features (e.g. movable seat pad). A model is a specific instance of the chair. (3) *Versions*: a set of products that have different design dates; usually the latest versions improve some features of the former versions (e.g. chair No. 14 and chair 214).

3.2 Population

3.2.1 Chairs

The chair is an object with a long history in Western culture. The first record of its existence dates back to the Neolithic: ceramic models were found in the Balkans region, representing women sitting in chairs (Cranz [1998] 2000). The oldest chair that survived into our era is the throne of the Pharaoh Tutankhamun (14th century B.C), from the Ancient Egypt. Both in Ancient Greece and in Ancient Rome two main types of chairs were used – the *thronus* (used for formal occasions), and the *cathedra* (used in domestic informal environments). In the Middle Ages, the chair evolution went into recession; the chairs were austere and heavy and were used merely for religious purposes or by higher social classes, while the peasants sat on the ground or on chests or benches. In the Renaissance the chair kept its role of social stratification but became lighter and portable on the one hand (in order to be used in social activities such as card games, concerts and plays) and sumptuous, comfortable, and decorated on the other hand (as an object that followed fashion trends). The 18th century is considered the golden age of the history of the chair, where numerous furniture styles have emerged, focused on comfort, luxury, fashion, decorative richness and artistic value.

Along four millennia, from the Ancient Egypt to the Industrial Revolution, the form of the chair hardly evolved. The chairs were predominantly made of wood and the evolution focused on the decoration and not so much on the structure of the chair. Over this period, the chair was a symbol of power, provided by the richness of the materials, the detail of the woodworking, and the majestic dimensions.

3.2.2 Modern chairs

A different paradigm in the history of chairs emerged with the Industrial Revolution. Modern chairs comprise the ones designed in the period between the mid-19th century and the present, and that were influenced by Modernism. These chairs also include reactions against Modernist principles (such as postmodernism), since they are still somehow influenced by Modernity (Fiell & Fiell [1993] 1994).[2]

Modern design has his origins in the Great Exhibition of 1851 in Britain. This launched the foundations of the Arts and Crafts Movement, which invoked a reaction to the ornamentation of machine-made objects (Pevsner [1936] 1991). Modern chairs follow the history of modern industrial design, which started with the Industrial Revolution in the mid-19th century (Bürdek 2005). This period is characterized by the transition of the chair from a craft production to an

[2] Some authors (Neves 2003; Design Museum 2009) refer to the chairs from this period as contemporary chairs, while others (Dampierre 2006) refer to Modern chairs as the ones designed in the 20th century.

industrial production, and from a craft product to a designed product (where design and manufacturing were not carried out anymore by a single person). Sitting habits have changed, since chairs were used without social distinctions in cafés, and the industrial work required people to spend more time sitting in chairs, as opposed to the agricultural work. Therefore, the chair became affordable and democratized, and it was no longer used by an elite. The richly decorated chairs conveying the status of luxury and ostentation were replaced by chairs that exploited new materials and manufacturing techniques, and that emphasized the formal above the symbolic.

The general principles of Modernism are: simple and abstract forms, functional and practical objects for everyday use, unity and harmony of forms and materials, honesty of materials and construction, universal and affordable products for everyone's use, and exploration of technological innovations and new materials (Fiell & Fiell [1993] 1994). Among these general principles, the last 150 years are characterized by a great diversity of chairs. This was caused by significant advances in manufacturing processes and materials (e.g. tubular steel, moulded plywood, and injection moulded plastics), and changes in taste, for e.g. with the redefinition of comfort (Fiell & Fiell [1997] 2012). Different trends in Modern chairs can be identified (Fiell & Fiell [1993] 1994), such as geometric abstraction – comprising rectilinear and symmetric forms and following the classic canons of proportion (e.g. Van der Rohe, Le Corbusier, Rietveld) and organic abstraction – inspired by natural forms (e.g. Alvar Aalto, Eero Saarinen, Eames).

The Modern period includes several movements and styles, marked by the Modernist principles but comprising several distinctive characteristics. In the second half of the 19th century, the *Arts and Crafts* movement proclaimed craft-produced, simple and functional objects, which would be ideally affordable (an ideal that was not accomplished, since craft production and the use of local materials increased the product cost). At the turn of the 19th and the 20th centuries, the *Art Noveau* style aimed at the combination of aesthetic and functional aspects, while contemplating some diversity – going from the straight and geometric forms of Charles Mackintosh to the curved and organic forms of Antoni Gaudí.

Later in the 1920s appeared the *De Stijl* style in the Netherlands, which made use of abstract basic shapes and primary colours (e.g. **Zig-Zag** chair). In opposition, the Art Deco style, named after the International Exhibition of 1925 held in France, was influenced by many different styles, and was characterized by luxury and superfluous decoration and the use of expensive materials (exemplified in Émile-Jacques Ruhlmann's chairs). The Bauhaus school in Germany (1919-1933) proclaimed the reconciliation between artisanal and industrial values, art and technique, and form and function. It defended the integrity of materials and manufacturing processes, rational forms, and affordable products. A new paradigmatic type of chair was developed during this period – the cantilever chair, made with tubular steel frame (e.g. **S33** chair).[3]

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[3] After a legal wrangling between Marcel Breuer and Mart Stam, the artistic copyrights of the cantilever chair were attributed to Stam in 1961.

After World War II, the development of new technologies, ergonomic concerns, and economic growth lead to great innovations in chair design. This is exemplified by chairs with sculptural forms, using multiple curvature modelled materials (e.g. **DCW** chair) and moulded plastic materials (e.g. **DAX** chair). The 1960s were marked by the *Pop Art* movement: a reaction against the rational austerity of "Good Design", in a decade of consumerism and youth fashions. The designs made use of bright colours, extravagant shapes, cheap materials (such as plastic), and search for technical innovation (e.g. **Panton** chair). During the 1970s, the *High-tech Design* was a result of a global recession and a reaction to the consumerism of the past decade; the style is marked by a return to rationalism, machine aesthetics, and austere and geometric shapes (e.g. **Omkstak** chair).

During the 1970s and 1980s, the *Postmodern Design* movement arises in opposition to the functionalism and perfectionism of the Modern movement. The designs gave preference to aesthetics beyond function, emphasizing the symbolic and metaphoric aspects, and reused classic design styles (e.g. **Queen Anne** chair). The mid-1980s is characterized by pluralism, fantasy, poetry, limited editions, and anti-rationalist designs dependent on fashion (e.g. **Louis 20** chair). In the late 1980s, the *Ecodesign* approach (also called *Green Design*) aimed to reduce the environmental impact of the products, by the use of recycled materials (e.g. **RCP2** chair), recyclable materials (e.g. **Louis 20** chair) or reused materials (e.g. **Wiggle** chair).

The chair is nowadays a ubiquitous object in the Western world. People spend most of their lives sitting in chairs, using it for several purposes (e.g. rest, work, eat, and wait) and in different environments (e.g. home, office, restaurant, and waiting room). However, the upright sitting posture is used by only about a third to half of the world population (Cranz [1998] 2000), in a reduced territory of the world. From the one hundred common upright human postures (divided into sitting, kneeling, crouching, squatting and standing), the sitting postures on a raised surface (in a chair or any other object that allows the same position, as benches and trunks) represent only eleven of them (Hewes 1955). Moreover, the posture of sitting on the floor is still common, such as the cross-legged sitting position in Turkey and in India, and the kneeling position with the legs folded underneath the thighs (called *seiza*) in Japan. Even in Western societies, people still sit on the ground on certain occasions (e.g. on the beach, in the garden, or on rugs or cushions).

> *"Since not all peoples sit in chairs, why do we? The answer to that question may never be known (...). One thing is certain: our chair habit was created, modified and nurtured, reformed and democratized in response to social - not genetic, anatomical, or even physiological - forces" (Cranz [1998] 2000, p.30).*

3.2.3 Portuguese Modern chairs

The Modernism in Portugal comprises the period from 1910 to the present (Martins 2001). Portuguese Modern chairs are characterized by simple and straight lines, elegant proportions, minimum decoration, use of natural and economic materials (such as wood, marsh straw and leather) and rationality in production (Parra 2011). These principles are reflected in the *Alentejana* chair – a well-known traditional Portuguese chair made with wooden frame and woven marsh straw seat.

The industrialization of the Portuguese chair occurs in the 1920s, with the mass production of furniture for hospitals and offices (Parra 2011). The revolutionary tubular steel chair was introduced in the 1930s; this material allowed the production of economical, lightweight, hygienic and industrialized chairs, being Longra one of the first companies to produce this type of chair. This material was applied in one of the most iconic Portuguese chairs – the **Gonçalo** chair, conceived by Gonçalo Rodrigues dos Santos in 1953 and produced by Arcalo.[4]

The decades of 1960s and 1970s were decisive for the institutionalization of design as an autonomous discipline in Portugal, thanks to the advances in its professionalization and education (Almeida 2009): the first school oriented specifically for design education (IADE) was created in 1969; the First exhibition of Portuguese Design occurred in 1971; and in 1974 the first degree in Design in public universities in Lisbon, and the Association of Portuguese Designers, were created. During this period, renowned designers developed projects of total design, where several design domains (such as interior, furniture, lighting, graphic, fashion, etc.) were integrated in the same project. This was the case of António Sena da Silva (1926-2001), António Garcia (1925-2015) and Daciano da Costa (1930-2005). These three designers created some of the most iconic Portuguese chairs (MUDE 2014), respectively: the Sena chair (1972), the Osaka chair (1970), and the Cortez series (1962). Also in this period, design became an important instrument in national industries, with three paradigmatic examples: José Espinho in Olaio, José Cruz Carvalho in Altamira, and Daciano da Costa in Longra (Parra 2011).

The 1980s presented a plurality of trends, exemplified by the rationality of the architect Siza Vieira and the post-modernist approach of the architect-designer Tomás Taveira. A new generation of Portuguese designers emerged in the late 1980s, including the designers Pedro Silva Dias, Fernando Sanchez Salvador, and the designers from the group Ex-Machina (1989-92): José Viana, Paulo Parra, Marco Sousa Santos, and Raul Cunca. The designs were frequently produced in limited editions, used craft techniques, and reissued decorative and sculptural forms, as observed in the iconic Mitsuhirato chair (Pedro Silva Dias, 1988). At the end of the 20th century, the Portuguese design presented a variety of directions, such as iconic, rationalist, sculptural, minimalist, playful and eclectic design (Neves 2003).

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[4] The authorship of this chair is controversial. There is a similar version called *Cadeira Portuguesa*, currently produced by Adico, and created in the 1930s by unknown author. The two versions are slightly different: the *Gonçalo* chair is overall slightly bigger, the armrest is more tilted and the back curvature is smaller. Moreover, it does not include stacking bumpers to protect finishing.

3.3 Subpopulations and Samples

3.3.1 Daciano Chairs

Daciano Henrique Monteiro da Costa (1930, Lisbon – 2005, Lisbon) was one of the most important Portuguese designers of the 20th century. His most relevant work was produced in the decades of 1960s and 1970s, when design was emerging as an autonomous discipline in Portugal. He graduated in painting at the Lisbon School of Fine Arts in 1961, but earlier in 1947 he started a long and fruitful career as designer, working with the architect Frederico George (1915-1994). He established his own design office in Lisbon in 1959. As a designer, he developed work in several domains, including interior design, exhibition design, furniture design, product design, costume design and scenography. He has an honorary doctorate in design from the University of Aveiro in 2003 and from the Technical University of Lisbon in 2004. As a teacher, he elaborated the curricular plan of the first degree in Design in the Faculty of Architecture of the Technical University of Lisbon in 1992, and contributed to the creation of the first Master in Design in Lisbon, in the same institution (2001).

The designs of Daciano are characterized by formal coherence, balance, proportion, and rigor in detail (Martins 2001; Bártolo & Ferrão 2016). Moreover, there was a concern to adequate designs to the context, being this an architectural space or technical, cultural and social context of the production, resources and consumers. His work is strongly influenced by the rationalism of modern design: conservative, classic and functional. Later, in the late 1980s, he combined modernist and postmodernist features: rationalism with humour, expected with unexpected. Daciano's principle "the forms of a function" (i.e., a function can be fulfilled by several forms) is expressed in some eclecticism demonstrated in his style, combining geometric and organic shapes, craft and industrial production). His designs are often a result of the addition of components (seat, back, legs, arms, etc.), where joints become essential. His design process comprises a composition of lines, surfaces and volumes.

Daciano had a pragmatic approach to the design process: the rationalization and subjacent rules ensured the overall coherence. The exception is used but never truly radical. His design process is clearly based on manual methods (sketches, models and prototypes). The rigor of the design method, the relation between school and industry, and the social responsibility were borrowed from the school UfG of Ulm – under the leadership of Tomás Maldonado (1956-67), and from the Bauhaus school lead by Hannes Meyer (1928-30).

The chairs designed by Daciano da Costa were part of two main types of projects (Martins 2001): on the one hand, limited editions of chairs were designed within interior architecture projects for specific contexts, such as hotels, auditoriums, casinos, restaurants and libraries. Daicano coordinated total design projects for emblematic public spaces, such as Fundação Calouste Gulbenkian, Biblioteca Nacional, and Centro Cultural de Belém. Many of the chairs produced in these contexts were later reedited for industrial production (e.g. the **Alvor-Grill** chair). On the other hand, chairs were designed as items of mass-produced furniture series for domestic or office uses, commissioned by Portuguese companies such as Metalúrgica da Longra, Móveis Sousa Braga, Olaio, Julcar, Larus and Interescritório. One of the most successful designs was the Cortez series – the first office furniture set designed by Daciano for Metalúrgica da Longra. Many of the designs were later reedited by other companies. A retrospective temporary exhibition of the work of Daciano da Costa took place in Fundação Calouste Gulbenkian in 2001 (from May 15 to June 24). His work can be seen in the permanent exhibitions of MUDE (in Lisbon) and Centre Pompidou (in Paris).

The subpopulation database contains 53 seats and can be consulted in **Appendix 3.A.1**. The seats were extracted from a single source: *Daciano da Costa: designer* – exhibition catalogue (Martins 2001). The sample was selected from this database.

Sample

The sample is composed by six multipurpose wooden frame chairs, designed by Daciano da Costa. There are two sample groups: Daciano Corpus [**DC**] and Daciano Existing [**DE**]. The chairs of the first group were designed for hotel restaurants and bedrooms in Portugal (detailed in **Appendix 3.B.1**), while the chair of the second group is part of a furniture series (called *Habitat 70*). All of the chairs were produced by the Portuguese company Móveis Sousa Braga, between 1966 and 1977. The frame of the chairs is made of solid wood and the seat and back panels are made of woven cane or are upholstered with leather or fabric cover. The datasheets of the chairs of the sample are shown below, in **Fig. 3.2.**

ID	**DC1**
Name	Alvor-Grill
Design	Daciano da Costa, 1966-68
Production	Móveis Sousa Braga, 1966-68, 1970
Commercialization	Metalúrgica da Longra, 1970
Materials	Pau-santo wood, leather upholstery
Techniques	Cutting, upholstering
Dimensions (mm)	W.615 x D.520 x H.780 x SH.427 (author's measurements)
Sampling criteria	Daciano wooden frame chair (Martins 2001; Neves 2003)
Image source	Author's photo

ID	**DC2**
Name	Alvor-Coffeeshop
Design	Daciano da Costa, 1966-68
Production	Móveis Sousa Braga, 1966-68
Commercialization	N/A
Materials	Wood, leather upholstery
Techniques	Cutting, upholstering
Dimensions (mm)	W.600 x D.478 x H.692 x SH.470 (author's measurements)
Sampling criteria	Daciano wooden frame chair (Martins 2001)
Image source	Author's photo

ID	**DC3**
Name	Palace
Design	Daciano da Costa, 1970-71
Production	Móveis Sousa Braga, 1970-71
Commercialization	Uniforma, 1992 (manufactured by Fago)
Materials	Andiroba wood, woven cane
Techniques	Cutting, hand weaving
Dimensions (mm)	W.618 x D.550 x H.775 x SH.431 (author's measurements)
Sampling criteria	Daciano wooden frame chair (Martins 2001; Neves 2003)
Image source	Author's photo

ID	**DC4**
Name	Penta-Restaurant
Design	Daciano da Costa, 1971-75
Production	Móveis Sousa Braga, 1971-75
Commercialization	N/A
Materials	Beech wood (darkened), fabric upholstery
Techniques	Cutting, upholstering
Dimensions (mm)	W.570 x D.480 x H.680 x SH.UNK (Neves 2003)
Sampling criteria	Daciano wooden frame chair (Martins 2001; Neves 2003)
Image source	(Martins 2001)

ID	**DC5**
Name	Tripeça
Design	Daciano da Costa, 1972-77
Production	Móveis Sousa Braga, 1972-77
Commercialization	N/A
Materials	Wood, fabric upholstery
Techniques	Cutting, upholstering
Dimensions (mm)	W.470 x D.423 x H.720 x SH.440 (author's measurements)
Sampling criteria	Daciano wooden frame chair (Martins 2001)
Image source	(Martins 2001)

ID	**DE6**
Name	Costureira
Design	Daciano da Costa, 1970
Production	Móveis Sousa Braga, 1970
Commercialization	Metalúrgica da Longra
Materials	Beech wood, leather upholstery
Techniques	Cutting, upholstering
Dimensions (mm)	W.456 x D.403 x H.679 x SH.430 (author's measurements)
Sampling criteria	Daciano wooden frame chair (Martins 2001)
Image source	Author's photo

Fig. 3.2 Daciano Chairs Sample

3.3.2 Jasper Chairs

Jasper Morrison (born 1959, London) is a well-known English designer. He received a Bachelor degree in Design in 1982, from Kingston Polytechnic (London), and a Master's degree in Design in 1985 from the Royal College of Art (London). In 2007 he was awarded an honorary doctorate in Design from Kingston University (formerly known as Kingston Polytechnic). He established his Office for Design in London in 1986, and currently has also offices in Tokyo and Paris. Morrison has been as a Royal Designer for Industry since 2001.

Morrison has a very concise guiding principle: to design 'normal' objects, for everyday life and for everyone's use. The designer believes that "special is usually less useful than normal" (Morrison [2002] 2006, p.233). This implies to design ordinary familiar objects that result from centuries of evolution, instead of groundbreaking designs often contemplating unnecessary changes promoted by marketing. 'Normal' objects are practical, durable, helpful, and honest. Moreover, he seeks for anonymous and affordable designs, ideals that are not always achievable.

The designer's style is guided by minimalism principles. Clean, simple and sexy forms produce visually light objects, with a balance between aesthetics, function and materials. Morrison regards design as a tool for improving daily life, a vision inspired in the Alexander's book 'A Pattern Language' (Alexander et al. 1977). His work is influenced by designers such as Dieter Rams, Eileen Gray, Le Corbusier, Jean Prouvé, and Franco Albini; and by styles such as Modern design, Scandinavian design, and Bauhaus style. He derives inspiration from the observation of real-life objects (Morrison 2017a)[5], and from illustrations, cartoons and typography.

The work of Jasper Morrison mostly addresses mass-produced products, including a wide range of products such as furniture, lighting, kitchenware, sanitaryware, electronics, and transportation. He has already collaborated with companies from all over the world, such as Cappellini, Alessi and Magis (Italy), Vitra (Switzerland), Muji (Japan), Samsung (South Korea), Camper (Spain), Maharam and Emeco (USA), SCP (United Kingdom), and Rowenta (Germany).

Jasper Morrison and Naoto Fukasawa promoted in 2006 the exhibition Super Normal in Axis Gallery, Tokyo. A retrospective exhibition of Morrison's work, called *Thingness*, took place between 2015 and 2017 in places such as the Tate Modern (London) and the Bauhaus Archive (Berlin). His work is exhibited in the most important museums of art and design around the world, including the Design Museum (London, UK), the Vitra Design Museum (Weil am Rhein, Germany), the Victoria & Albert Museum (London, UK) and MoMA (New York, USA).

The subpopulation database contains 55 seats and is available in **Appendix 3.A.2**. The subpopulation was extracted from one source: the official web page of Jasper Morrison (Morrison 2017b). The sample was selected from this database.

[5] (Morrison 2017a) is a selection of handcrafted artefacts of everyday rural life in Portugal. It illustrates pure and beautiful objects that are derived from trial-and-error evolution and simple resources.

Sample

The sample is constituted by six multipurpose wooden frame chairs, designed by Jasper Morrison. The sample is divided into two groups: Jasper Corpus [**JC**] and Jasper Existing [**JE**]. The chairs from the first group were designed for mass production, between 1988 and 2011, for three different companies: three chairs for Vitra, one for Capellini, and one for Murani. The chair from the second group was designed to a specific context: the refectory of the *Couvent de La Tourette*, in France, designed by the architect Le Corbusier. The frame of the chairs is made of solid wood or plywood, and the seat and back panels are made of wood or plastic. More details concerning the chairs can be consulted in **Appendix 3.B.1**. The datasheets of the chairs of the sample are shown below, in **Fig. 3.3.**

ID	**JC1; ICB22**
Name	Ply
Design	Jasper Morrison, 1988
Production	Vitra, 1989-UNK
Commercialization	N/A
Materials	Plywood
Techniques	Cutting
Dimensions (mm)	W.365 x D.470 x H.845 x SH.475
Sampling criteria	**JC1**: Morrison wooden frame chair (Morrison 2017b); **ICB22**: open-back chair (Design Museum 2009; VDM [1996] 2013)
Image source	(Morrison 2017b)

ID	**JC2**
Name	Basel
Design	Jasper Morrison, 2008
Production	Vitra, 2008-
Commercialization	Vitra DE, 340.00€
Materials	Beech wood, ASA plastic
Techniques	UNK
Dimensions (mm)	W.425 x D.470 x H.800 x SH.460
Sampling criteria	Morrison wooden frame chair (Morrison 2017b)
Image source	(Vitra 2016)

ID	**JC3**
Name	Bac Armchair
Design	Jasper Morrison, 2009
Production	Cappellini[6], 2009-
Commercialization	Various
Materials	Ash wood, ash plywood
Techniques	UNK
Dimensions (mm)	W.525 x D.510 x H.730 x SH.455
Sampling criteria	Morrison wooden frame chair (Morrison 2017b)
Image source	(Cappellini 2016)

[6] Capellini and Cassina belong to the Poltrona Frau Group.

ID	**JC4**
Name	HAL
Design	Jasper Morrison, 2007-10
Production	Vitra, 2010-
Commercialization	Vitra DE, 516.00€
Materials	Oak wood, polypropylene
Techniques	Moulding
Dimensions (mm)	W.475 x D.510 x H.795 x SH.435
Sampling criteria	Morrison wooden frame chair (Morrison 2017b)
Image source	(Vitra 2016)

ID	**JC5**
Name	Lightwood
Design	Jasper Morrison, 2011
Production	Maruni, 2011-
Commercialization	Various
Materials	Maple wood, polyester mesh
Techniques	UNK
Dimensions (mm)	W.468 x D.467 x H.782 x SH.450
Sampling criteria	Morrison wooden frame chair (Morrison 2017b)
Image source	(Maruni 2016)

ID	**JE6**
Name	La Tourette
Design	Jasper Morrison, 1997
Production	Hubert Weinzierl, 1997, 2015-
Commercialization	Hubert Weinzierl, 1800.00€
Materials	Oak wood
Techniques	UNK
Dimensions (mm)	W.410 x D.453 x H.765 x SH.470
Sampling criteria	Morrison wooden frame chair (Morrison 2017b)
Image source	(Hubert Weinzierl 2016)

Fig. 3.3 Jasper Chairs Sample

3.3.3 Iconic Chairs

Iconic chairs are design classics, successful and representative landmarks which survived the test of time (Design Museum 2009). Iconic designs are influential, inspirational, and innovative (Sibthorp & Quin 2012). Such designs are exhibited in famous art and design museums around the world, and enhance the popularity of their designers. Chairs were first exhibited in an organized fashion at New York's MoMA in the 1930s. They are also part of several compendia which illustrate the history of chairs. The quality of iconic chairs may be arguable, since as Papanek (1995) points out, some of the designs are merely 'fetish symbols', uncomfortable and egocentric, and are being reissued after not being in production for a long time (e.g. **Zig-Zag** chair).

However, other iconic designs are comfortable, simple and elegant, and have been continuously in production for over more than half a century (e.g. **Ant** chair).

The subpopulation of iconic chars is divided into two groups: international iconic chairs and Portuguese iconic chairs. The database of the first group contains 639 seats and can be consulted in **Appendix 3.A.3.** This subpopulation was extracted from six sources, comprising both museum collections and chair compendia:

1) *Fifty Chairs that Changed the World*: selection of 50 Modern seats from a design museum collection (Design Museum 2009);
2) *100 Masterpieces from the Vitra Design Museum Collection*: selection of 86 Modern seats from a design museum collection (VDM [1996] 2013);
3) *Chairs: 20th-Century Classics*: compendium of 96 Modern seats (Sibthorp & Quin 2012);
4) *1000 Chairs*: compendium of 1000 Modern seats (Fiell & Fiell [1997] 2012);
5) *Chairs*: selection of 144 seats from the book *1000 Chairs* (Fiell & Fiell 2002) [7];
6) *Modern Chairs*: compendium of 98 Modern seats (Fiell & Fiell [1993] 1994).

This subpopulation includes a wide formal, structural and material diversity. The most represented designers are Gerrit Rietveld (1888–1964), Alvar Aalto (1898–1976), Marcel Breuer (1902–1981), Charles and Ray Eames (1907–1978; 1912–1988), Verner Panton (1926–1998), Hans Wegner (1914–2007), Phillipe Starck (born 1949), and Ron Arad (born 1951). Some of the designers are also architects, such as Alvar Aalto, or painters, such as Ray Eames. The most represented companies are Capellini, Cassina and Zanotta (Italy), Fritz Hansen (Denmark), Herman Miller and Knoll (USA), Vitra (Switzerland), and Thonet (Germany and Austria).

The database of the second group contains 85 seats and be consulted in **Appendix 3.A.4**. The seats were retrieved from seven sources, including Portuguese and International design exhibitions and competitions, some specific to chair design:

1) *Sentar Portugal: 23 Cadeiras da Colecção Paulo Parra*: Portuguese chair design exhibition (Parra 2011);
2) *Como se Pronuncia Design em Português?*: Portuguese design exhibition (Coutinho 2015);
3) *Art on Chairs - International Design Competition*: international chair design competition – selection from the 1st to the 4th places (Branco 2012);
4) *Design and Design Award – 2012*: international design competition (Praquin 2013);

[7] This selection contains six chairs which are not included in the book *1000 Chairs*.

5) *Ordem de Compra: O design e a indústria portugueses na economia actual – exemplos de sucesso*: Portuguese design exhibition (Experimentadesign 2011);

6) *Best of: 180 Produtos de Design Português*: compendium of Portuguese design (Centro Português de Design 2003);

7) *MUDE - Permanent Exhibition*: international design exhibition, in 1999 and in 2014 (Brunhaumer, Capelo & Museu do Design 1999; MUDE 2014).

The most represented Portuguese designers in the database are Daciano da Costa (1930-2005), Pedro Silva Dias (born 1963), Marco Sousa Santos (born 1962), and Paulo Parra (born 1961). The most represented Portuguese furniture companies are Julcar (founded in 1980), Metalúrgica da Longra (1920-1993), and Móveis Olaio (1886-1998). A source which was not used but is worth mentioning is the compendium of Portuguese Modern chairs of Neves (2003). The sample was selected from the databases of the two groups of iconic chars.

Sample

The sample contains chairs from 5 of the 13 aforementioned sources: four sources of the international iconic subpopulation (Design Museum 2009; VDM [1996] 2013; Sibthorp & Quin 2012; Fiell & Fiell [1997] 2012), and one source of the Portuguese iconic subpopulation (Parra 2011).

The sample is composed by two groups: Iconic Corpus [**IC**] and Iconic Existing [**IE**]. The former group is further subdivided, in relation to the main selection criteria: technology breakthroughs [**ICA**] and ontology gaps [**ICB**]. The first criteria address chairs that, according to the mentioned sources, introduced a relevant technological innovation. The second criteria comprised chairs representing types in the ontology (described in the chapter **Multipurpose Chair Ontology**) that were not addressed by the first group. This approach followed the theoretical sampling method (Marshall 1996), since it comprised an iterative process between the choice of the sample individuals and the development of the ontology. The selection criteria of the **IE** group comprised the six most recent multipurpose chairs mentioned in one source (Design Museum 2009), excluding the Samouraï chair (that did not have enough information available). A stool was selected from the same source as a proof of concept, in order to demonstrate that a system able to generate chairs can be easily adapted to generate stools (by removing the backrest). Incidentally, the selected design (Stool 60) was later adapted to a chair (Chair 65).

The sample comprises 32 multipurpose iconic chairs, divided as follows: 13 from the group **ICA**, 13 from the group **ICB**, and six from the group **IE**. The latter group also includes one stool. The chairs were designed by 29 designers; the ones contributing with more than one chair are Charles and Ray Eames (with three chairs) and Jasper Morrison (with two chairs). The chairs were produced by 12 companies; the ones most represented are Herman Miller and Vitra (four chairs each), Fritz Hansen, Magis, Knoll, Kartell and Thonet GmbH (two chairs each).

The chairs contemplate a wide variety of materials (wood, metal, plastic, textile and paper), comprising different configurations (solid, tubular and rod profile, sheet, ply, liquid, etc.). Different techniques were employed, including cutting, bending, moulding, weaving and upholstering. Many of the designs are part of a design collection, which includes armchairs, children's chairs, rocking chairs, stools, benches, desks and tables. They also comprise several options, including modular parts (e.g. different bases), colours, and materials. The prices of the chairs range from 77.50€ to 4588.00€.

This sample includes several types of chairs: the legs vary from one to four, the seats have different shapes (round, square or trapezoid), there are several inner back frame configurations (with horizontal or/and vertical elements, no elements or one solid element), different stretchers and base configurations (e.g. H-, U-, and X-shaped) can be found, and there are chairs with or without armrests.

The design process contemplated several sources of inspiration, such as chairs from other designers, other objects, design styles, sculptures and flowers. Moreover, the design goals were diverse, focusing on aspects such as form and structure, materials and manufacturing technologies, ergonomics and comfort, aesthetics, price, weight, durability, assemblage, and additional functions (e.g., stackable and outdoor use). The designs, besides the Modern style, can be classified according to other styles, such as the Mid-century Modern, Danish Modern, Scandinavian Modern, Italian Modern, De Stijl, Pop art, high-tech and postmodernism.

More details concerning the chairs of the sample can be consulted in **Appendix 3.B.1**. The datasheets of the chairs of the sample are shown below, in **Fig. 3.4**, and the timeline of the chairs is illustrated in **Fig. 3.5**.

ID	**ICA1; TC1**
Name	214
Design	Michael Thonet, 1859
Production	Thonet GmbH, 1859-
Commercialization	Thonet GmbH DE, 696.15€
Materials	Beech wood, woven cane
Techniques	Bending, hand weaving
Dimensions (mm)	W.430 x D.520 x H.840 x SH.460
Sampling criteria	**ICA1**: 1st Bentwood frame (Design Museum 2009; Fiell & Fiell [1997] 2012; VDM [1996] 2013); **TC1**: Corpus of Thonet Grammar (Barros, Duarte & Chaparro 2011)
Image source	(Thonet GmbH 2016)

ID	**ICA2**
Name	S33
Design	Mart Stam, 1926
Production	Thonet GmbH, 1926-
Commercialization	Thonet GmbH DE, 999.60€
Materials	Tubular steel, leather
Techniques	Bending
Dimensions (mm)	W.500 x D.640 x H.840 x SH.460
Sampling criteria	1st Cantilever chair (Design Museum 2009; Fiell & Fiell [1997] 2012; Sibthorp & Quin 2012)
Image source	(Thonet GmbH 2016)

ID	**ICA3**
Name	Zig-Zag
Design	Gerrit Rietveld, 1932-34
Production	Cassina, 1973-
Commercialization	Various
Materials	Cherry wood
Techniques	Cutting
Dimensions (mm)	W.370 x D.430 x H.740 x SH.430
Sampling criteria	2nd Wood cantilever chair (Design Museum 2009; Fiell & Fiell [1997] 2012; Sibthorp & Quin 2012; VDM [1996] 2013)
Image source	(Cassina 2016)

ID	**ICA4**
Name	Landi
Design	Hans Coray, 1938
Production	Vitra, 2015-
Commercialization	Vitra DE, 446.00€
Materials	Aluminium profile and sheet
Techniques	Bending, compression moulding
Dimensions (mm)	W.515 x D.650 x H.795 x SH.475
Sampling criteria	1st Shell in hard material (Design Museum 2009; Fiell & Fiell [1997] 2012; VDM [1996] 2013)
Image source	(Vitra 2016)

ID	**ICA5**
Name	DCW
Design	Charles & Ray Eames, 1945
Production	Herman Miller, 1949-
Commercialization	Herman Miller, $889.00
Materials	Birch plywood
Techniques	Compression moulding
Dimensions (mm)	W.502 x D.552 x H.730 x SH.451
Sampling criteria	1st Moulded plywood in compound curves (Design Museum 2009; Fiell & Fiell [1997] 2012; Sibthorp & Quin 2012; VDM [1996] 2013)
Image source	(Herman Miller 2016)

ID	**ICA6**
Name	DAX
Design	Charles & Ray Eames, 1948-1950
Production	Herman Miller, 1950-1989, 2004-
Commercialization	Herman Miller, $459.00
Materials	Tubular steel, polypropylene
Techniques	Bending, moulding
Dimensions (mm)	W.635 x D.610 x H.800 x SH.457
Sampling criteria	1st Shell in fibreglass-reinforced plastic (VDM [1996] 2013)
Image source	(Herman Miller 2016)

ID	**ICA7**
Name	DKR
Design	Charles & Ray Eames, 1951
Production	Herman Miller, 1951-
Commercialization	Herman Miller, $779.00
Materials	Steel rod and wire
Techniques	Bending
Dimensions (mm)	W.483 x D.540 x H.832 x SH.455
Sampling criteria	1st Shell in wire mesh (Design Museum 2009; Fiell & Fiell [1997] 2012; VDM [1996] 2013)
Image source	(Herman Miller 2016)

ID	**ICA8**
Name	Tulip (chair)
Design	Eero Saarinen, 1955-56
Production	Knoll, 1956-
Commercialization	Knoll, $1438.00
Materials	Die-cast aluminium, fibreglass reinforced plastic
Techniques	Moulding
Dimensions (mm)	W.508 x D.540 x H.813 x SH.470
Sampling criteria	1st "Wineglass" pedestal base (Design Museum 2009; Fiell & Fiell [1997] 2012; Sibthorp & Quin 2012; VDM [1996] 2013)
Image source	(Knoll 2016)

ID	**ICA9**
Name	Superleggera
Design	Gio Ponti, 1951-57
Production	Cassina, 1957-
Commercialization	Various
Materials	Ash wood, woven cane
Techniques	Hand weaving
Dimensions (mm)	W.410 x D.450 x H.830 x SH.460
Sampling criteria	Super-lightweight chair (Design Museum 2009; Fiell & Fiell [1997] 2012; Sibthorp & Quin 2012; VDM [1996] 2013)
Image source	(Cassina 2016)

ID	**ICA10**
Name	Polyside
Design	Robin Day, 1962-63
Production	Hille, 1963-
Commercialization	Hille, £73.00
Materials	Tubular steel, Polypropylene
Techniques	Bending, injection moulding
Dimensions (mm)	W.530 x D.505 x H.745 x SH.440
Sampling criteria	1st Polypropylene shell (Design Museum 2009; Fiell & Fiell [1997] 2012; Sibthorp & Quin 2012)
Image source	(Hille 2016)

ID	**ICA11**
Name	Bofinger
Design	Helmut Bätzner, 1964-65
Production	Wilhelm Bofinger, 1966-1984
Commercialization	N/A
Materials	Polyester
Techniques	Compression moulding
Dimensions (mm)	W.525 x D.535 x H.750 x SH.440
Sampling criteria	1st One-piece mass-produced plastic chair (Fiell & Fiell [1997] 2012; VDM [1996] 2013)
Image source	(V&A 2016)

ID	**ICA12**
Name	Universale
Design	Joe Colombo, 1965-67
Production	Kartell, 1968-UNK
Commercialization	N/A
Materials	Polypropylene
Techniques	Injection moulding
Dimensions (mm)	W.420 x D.500 x H.710 x SH.430
Sampling criteria	1st Adult-sized injection-moulded chair (Design Museum 2009; Fiell & Fiell [1997] 2012)
Image source	(Kartell 2014)

ID	**ICA13**
Name	Panton
Design	Verner Panton, 1959-67[8]
Production	Vitra, 1999-
Commercialization	Vitra DE, 229.00€
Materials	Polypropylene
Techniques	Injection moulding
Dimensions (mm)	W.500 x D.610 x H.830 x SH.410
Sampling criteria	1st One-piece cantilever chair (Design Museum 2009; Fiell & Fiell [1997] 2012; Sibthorp & Quin 2012; VDM [1996] 2013)
Image source	(Vitra 2016)

[8] The design date is not consensual among sources, mentioning: the design date – 1959-60 (Fiell & Fiell [1997] 2012), the production date – 1968 (Design Museum 2009), or the development period between 1957 and 1967 (VDM [1996] 2013). In 1999 the polypropylene version was launched.

ID	**ICB14**
Name	Wishbone
Design	Hans Wegner, 1949
Production	Carl Hansen & Son, 1950-
Commercialization	Various
Materials	Oak wood, woven paper cord
Techniques	Steam-bending, hand weaving
Dimensions (mm)	W.550 x D.510 x H.750 x SH.450
Sampling criteria	Spindle back (Fiell & Fiell [1997] 2012; Sibthorp & Quin 2012)
Image source	(Carl Hansen & Søn 2016)

ID	**ICB15**
Name	Antelope
Design	Ernest Race, 1950
Production	Race Furniture, 1951-
Commercialization	Race Furniture, £356.00 +VAT
Materials	Steel rod, Gabon plywood
Techniques	Bending, moulding
Dimensions (mm)	W.500 x D.530 x H.800 x SH.450
Sampling criteria	Parallel stretcher (Design Museum 2009; Fiell & Fiell [1997] 2012; Sibthorp & Quin 2012)
Image source	(Race Furniture 2016)

ID	**ICB16**
Name	Bellevue
Design	André Bloc, 1951
Production	UNK
Commercialization	N/A
Materials	Tubular steel, plywood
Techniques	Bending
Dimensions (mm)	W.395 x D.490 x H.825 x SH.420
Sampling criteria	U-shaped stretcher (VDM [1996] 2013)
Image source	(VDM [1996] 2013)

ID	**ICB17**
Name	Ant
Design	Arne Jacobsen, 1952
Production	Fritz Hansen, 1952-
Commercialization	Fritz Hansen, 455.00€
Materials	Tubular steel, beech plywood
Techniques	Bending, compression moulding
Dimensions (mm)	W.510 x D.480 x H.780 x SH.440
Sampling criteria	3-Legged chair (Fiell & Fiell [1997] 2012; Sibthorp & Quin 2012; VDM [1996] 2013)
Image source	(Fritz Hansen 2016)

ID	**ICB18**
Name	Swag Leg (DAF)
Design	George Nelson, 1956-58
Production	Herman Miller, 1958-64, 2006-
Commercialization	Herman Miller, $599.00
Materials	Tubular steel, polypropylene
Techniques	Swaging, moulding (Eames patented)
Dimensions (mm)	W.711 x D.559 x H.813 x SH.457
Sampling criteria	Pedestal 4-star base (Fiell & Fiell [1997] 2012; Sibthorp & Quin 2012)[9]
Image source	(Herman Miller 2016)

ID	**ICB19**
Name	PK9
Design	Poul Kjærholm, 1960
Production	Fritz Hansen, 1960-
Commercialization	Fritz Hansen, 4588.00€
Materials	Steel bar, leather upholstery & nylon (filling)
Techniques	Upholstering
Dimensions (mm)	W.560 x D.600 x H.760 x SH.430
Sampling criteria	Pedestal 3-star base (Sibthorp & Quin 2012)
Image source	(Fritz Hansen 2016)

ID	**ICB20**
Name	Spaghetti
Design	Giandomenico Belotti, 1979
Production	Alias, 1979-
Commercialization	Alias
Materials	Tubular steel, PVC plastic
Techniques	Hand weaving
Dimensions (mm)	W.400 x D.510 x H.840 x SH.460
Sampling criteria	H-shaped stretcher (Fiell & Fiell [1997] 2012)
Image source	(Alias 2016)

ID	**ICB21**
Name	S
Design	Tom Dixon, 1988
Production	Cappellini, 1992-
Commercialization	Various
Materials	Tubular steel, woven marsh straw
Techniques	Bending, hand weaving
Dimensions (mm)	W.500 x D.420 x H.1020 x SH.470
Sampling criteria	Cantilever with round base (Design Museum 2009; Fiell & Fiell [1997] 2012; Sibthorp & Quin 2012)
Image source	(Cappellini 2016)

[9] There is a mistake in (Sibthorp & Quin 2012): the chair in the picture is DAF (not MAA). According to the George Nelson Foundation website (http://www.georgenelsonfoundation.org), DAF/MAF chairs have a fixed back and DAA/MAA chairs have a movable back.

ID	**ICB23**
Name	RCP2
Design	Jane Atfield, 1992
Production	Made of Waste, 1996-UNK
Commercialization	N/A
Materials	High-density polyethylene sheet (recycled bottles)
Techniques	Cutting
Dimensions (mm)	W.373 x D.435 x H.810 x SH.UNK
Sampling criteria	Double 4-legged chair (Fiell & Fiell [1997] 2012)
Image source	(V&A 2016)

ID	**ICB24**
Name	Magic
Design	Ross Lovegrove, 1997
Production	Fasem, 1997-UNK
Commercialization	N/A
Materials	Tubular steel, polyurethane
Techniques	Moulding
Dimensions (mm)	W.560 x D.570 x H.800 x SH.470
Sampling criteria	Reverse cantilever chair (Fiell & Fiell [1997] 2012)
Image source	(MoMA 2016)

ID	**ICB25**
Name	Chair_One
Design	Konstantin Grcic, 2003
Production	Magis, 2003-
Commercialization	Herman Miller, $534.50
Materials	Aluminium profile, die-cast aluminium
Techniques	Moulding
Dimensions (mm)	W.550 x D.590 x H.820 x SH.450
Sampling criteria	X-shaped back chair (Design Museum 2009)
Image source	(Herman Miller 2016)

ID	**IPCB26**
Name	Gonçalo
Design	Gonçalo Santos, 1953
Production	Arcalo, 1953-
Commercialization	Arcalo, 77.50€
Materials	Tubular steel, steel sheet
Techniques	Bending
Dimensions (mm)	W.520 x D.540 x H.720 x SH.420
Sampling criteria	Semicircular seat (Parra 2011)
Image source	(Arcalo 2016)

ID	**IE27**
Name	Omkstak
Design	Rodney Kinsman, 1971
Production	OMK Design, mid-1990s[10]
Commercialization	OMK Design, £108.00
Materials	Tubular steel, steel sheet
Techniques	Bending, Pressing
Dimensions (mm)	W.555 x D.495 x H.750 x SH.450
Sampling criteria	Six chairs of Design Museum (2009)
Image source	(OMK Design 2016)

ID	**IE28**
Name	Wiggle
Design	Frank Gehry, 1972
Production	Vitra, 1986-
Commercialization	Vitra DE, 757.00€
Materials	Cardboard & hardboard sheet
Techniques	UNK
Dimensions (mm)	W.350 x D.610 x H.870 x SH.430
Sampling criteria	Six chairs of Design Museum (2009)
Image source	(Vitra 2016)

ID	**IE29**
Name	Queen Anne
Design	Robert Venturi, 1979-84
Production	Knoll, 1984-UNK
Commercialization	N/A
Materials	Maple plywood
Techniques	Cutting, bending
Dimensions (mm)	W.676 x D.603 x H.978 x SH.473
Sampling criteria	Six chairs of Design Museum (2009)
Image source	(MoMA 2016)

ID	**IE30**
Name	Louis 20 (side chair)
Design	Philippe Starck, 1991
Production	Vitra, 1991-UNK
Commercialization	N/A
Materials	Tubular aluminium, polypropylene
Techniques	Bending, blow moulding
Dimensions (mm)	W.470 x D.546 x H.843 x SH.467
Sampling criteria	Six chairs of Design Museum (2009)
Image source	(DM 2016)

[10] The OMK Design company sources the components from different factories of northern Italy and makes the assembly and painting in their warehouse in UK.

ID	**IE31**
Name	FPE
Design	Ron Arad, 1997
Production	Kartell, 1997-UNK
Commercialization	N/A
Materials	Aluminium profile, polypropylene
Techniques	Injection moulding
Dimensions (mm)	W.430 x D.590 x H.780 x SH.460
Sampling criteria	Six chairs of Design Museum (2009)
Image source	(MoMA 2016)

ID	**IE32**
Name	Air-Chair
Design	Jasper Morrison, 1999
Production	Magis, 2000-
Commercialization	Herman Miller, $174.75
Materials	Polypropylene & fibreglass
Techniques	Air moulding
Dimensions (mm)	W.490 x D.510 x H.775 x SH.470
Sampling criteria	Six chairs of Design Museum (2009)
Image source	(Herman Miller 2016)

ID	**ISE1**
Name	Stool 60
Design	Alvar Aalto, 1932-33
Production	Artek, 1933-
Commercialization	Artek
Materials	Birch plywood, birch wood
Techniques	Bending, cutting
Dimensions (mm)	W.380 x D.380 x H.440 x SH.440
Sampling criteria	Stool of Design Museum (2009)
Image source	(Artek 2016)

Fig. 3.4 Iconic chairs sample

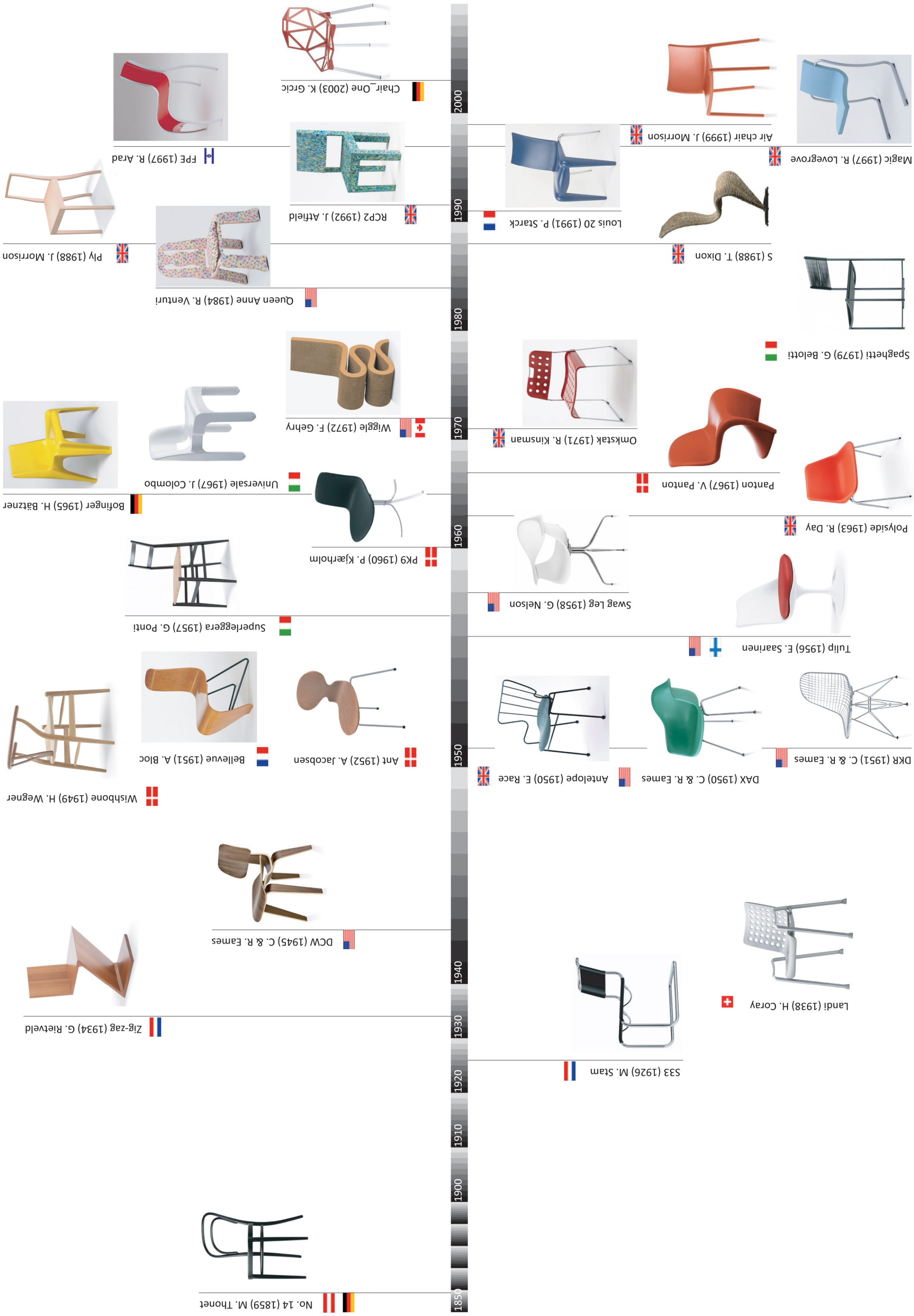

Fig. 3.5 Iconic chairs timeline

3.3.4 Thonet Chairs

Thonet GmbH is a furniture manufacturing company, based in Frankenberg (Germany). The history of the company dates back to 1819, when Michael Thonet (1796, Boppard, Germany – 1871, Vienna, Austria), an innovative cabinetmaker, established his woodworking shop in Boppard (Germany). Thonet invented a wood bending technique, which made his furniture an international success. In 1842 Thonet moves to Vienna, and in 1853 the company was transferred to his sons under the name Gebrüder Thonet. One of his sons, August Thonet (1829, Boppard, Germany – 1910, Arco, Italy), managed the family business from 1869 to 1886. The company established seven factories across Europe, from 1856 to 1889, being the last one based in Frankenberg. In 1976, Thonet was divided in two independent companies, one German and one Austrian, and in 2006 the German company Gebrüder Thonet became Thonet GmbH (Thonet GmbH 2015). Nowadays the company produces a series of well-known designs, including classic bentwood and tubular steel furniture.

The Thonet company introduced in the mid-19th century a series of breakthroughs: an innovative method of bending wood, a pioneering mass production process (including an assembly line), and an innovative marketing strategy (including catalogues available in several languages and the participation in international fairs). The Thonet bentwood furniture was lightweight, elegant and durable; was made of few components, and was easy to disassemble. The designs were meant to be used in public places such as cafés and restaurants. The furniture (including chairs, armchairs, rocking chairs, office chairs, stools, canapés and tables) was a commercial success: in 1912 two million products were sold worldwide. Thonet remains as a great influence in product design history, concerning style, production method and marketing principles (Barros 2015).

The chair No. 14 (produced nowadays by Thonet GmbH as 214) was a sales success[11]. Thirty-six disassembled chairs (composed of six bentwood components) could be packed in a one cubic meter box, which represented a revolutionary packing method and made the transportation more economical. The chair won the bronze medal at the Great Exhibition in London (1851) and the gold medal at the *Exposition Universelle* in Paris (1867). The No. 14 is considered the first Modern chair (Barros 2015), representing the transition from craft to mass production.

The Thonet bentwood chairs share similar principles and appearance. The Thonet chair style (Barros, Duarte & Chaparro 2011) is characterized by simple and functional lines, light and elegant forms, and organic shapes (using slight 3D curves). The style is influenced by the simplification principles of the Biedermeier style and the elegant curves of the Queen Anne style (Barros 2015). The Thonet chairs are characterized by a reduced number of components, usually including: an organically shaped pieced comprising the back leg and back outer frame; the front legs; a seat rounded rail and panel; round stretchers; and a back inner frame. The chairs are 4-

[11] Between 1859 and 1914, forty millions of chairs No. 14 were produced (Fiell & Fiell [1993] 1994).

legged, and can have or not armrests. The materials employed are beech bentwood in the frame and woven cane or laminated veneer in the seat panel. The chairs are affordable, as they have few components, are easily disassembled, are industrially produced, and use standardized elements (applying the principle of modularity).

The subpopulation database contains six chairs and can be consulted in **Appendix 3.A.5**. The subpopulation was extracted from a single source: the corpus of the *Thonet Chair Design Grammar* (Barros, Duarte & Chaparro 2011). The sample was selected from this database.

Sample

The sample comprises four multipurpose wooden frame chairs manufactured by the company Thonet GmbH. The sample is composed by two groups: Thonet Corpus [**TC**] and Thonet Existing [**TE**]. The first group has three chairs, which belong to the corpus of the *Thonet Chair Design Grammar* (Barros, Duarte & Chaparro 2011). From the original corpus of six chairs, the chairs No. 1, No. 4, and No. 16 were not selected, because they are not currently manufactured by Thonet GmbH. The selected chairs are produced nowadays by Thonet GmbH with the names 214, 215 and 218, but originally they were called No. 14, No. 15 and No. 18, respectively. The chair from the second group is a redesign of the chair 214 (Barros 2015)[12], and was launched on the occasion of the 150th birthday of the chair No. 14. The chairs of the sample can be considered to be part of the same family, since the distinguishing feature is the backrest inner frame (except the last chair which additionally does not have stretchers). More details can be consulted in **Appendix 3.B.1**. The datasheets of the chairs of the sample are shown below, in **Fig. 3.6**.

ID	**TC2**
Name	215
Design	Michael Thonet, 1859
Production	Thonet GmbH, 1859-
Commercialization	Thonet GmbH DE
Materials	Beech wood, woven cane
Techniques	Bending, hand weaving
Dimensions (mm)	W.430 x D.520 x H.840 x SH.460
Sampling criteria	Corpus of Thonet Grammar (Barros, Duarte & Chaparro 2011)
Image source	(Thonet GmbH 2016)

[12] The chair 214 was also redesigned in 2011 by Robert Stadler. It is currently produced by Thonet GmbH with the name 107. This chair contains more radical formal innovations, in order for all the pieces to be machine-made.

ID	**TC3**
Name	218
Design	August Thonet, 1876
Production	Thonet GmbH, 1876-
Commercialization	Thonet GmbH DE
Materials	Beech wood, woven cane
Techniques	Bending, hand weaving
Dimensions (mm)	W.430 x D.520 x H.840 x SH.460
Sampling criteria	Corpus of Thonet Grammar (Barros, Duarte & Chaparro 2011)
Image source	(Thonet GmbH 2016)

ID	**TE4**
Name	Muji No. 14
Design	James Irvine, 2009
Production	Muji (producer), Thonet GmbH (manufacturer), 2009-
Commercialization	Muji, ¥33,000.00
Materials	Beech wood, beech plywood
Techniques	Bending, cutting
Dimensions (mm)	W.415 x D.510 x H.850 x SH.460
Sampling criteria	Redesign of the chair Thonet 214 (Barros 2015)
Image source	(Muji 2016)

Fig. 3.6 Thonet chairs sample

3.4 Conclusion

This chapter presented the study population, the subpopulations and the sample. The chapter addressed the second stage of the computational model described in the **Introduction** chapter, featuring a product class as a case study. The population is characterized by symmetric multipurpose Modern chairs. It comprises chairs designed in the period between 1850 and the present, in the Western world.

Four subpopulations were selected from the population; comprising different goals addressed in four versions of the model. The subpopulations are: (1) multipurpose wooden frame chairs of a Portuguese designer; (2) multipurpose wooden frame chairs of an English designer; (3) iconic chairs (international and Portuguese); and (4) wooden chairs of a German manufacturing company. The seats comprising the subpopulations were stored in a database, which specify the designer, the design date, the producer, and the product type.

A sample of 46 chairs and one stool was selected from the four subpopulations: 6 chairs of the first subpopulation, 6 chairs of the second subpopulation, 32 chairs and 1 stool of the third subpopulation, and 4 chairs of the fourth subpopulation. There are two chairs that belong to two subpopulations. The sample groups comprised different selection criteria: the first two groups address two designers' styles, considering a more restricted type of multipurpose chair (wooden frame chairs). The third group was intended to cover a large variety of types, including 1 to 4 legged chairs, arm and armless chairs, different seat shapes, and different back, stretchers and base configurations. The forth group addressed a design family manufactured by a company. The chairs from the sample are stored in a database, and classified according to several aspects: design and production details, functions, materials and technologies, dimensions, product type, recyclability and packaging, and related products.

The main contribution of this chapter is a set of databases of seats and chairs. The study addressed international chair design, and gave a particular emphasis to Portuguese chair design, more specifically to one of the most influential Portuguese designers – Daciano da Costa. The databases are formatted in Excel spreadsheets.

It is recommended for future work to implement the databases in a database management system, in order to allow a flexible visualization of data. An online interface would make it accessible and enable users to obtain the features list of particular chair or search for chairs with particular features. It would be also productive to implement a collaborative system, in order to enhance the feasibility of data and promote the database update and development.

Other recommendations are related to the extension of the database, in order to embrace further categories and chairs. On the one hand, more subcategories can be included in existing categories, such as: production time and number of produced units (in production); modularity and type of movement (in functions); certification, copyright, design awards, and videos (in documents); and chair accessories, such as seat/back pads and glides (in product options).

On the other hand, more chairs could be included. Although an effort has been made to cover the main types of chairs, there are existing designs which address types currently not contemplated by the sample, such as:

1) *1-Legged cantilever chair:* Bone chair, designed by Ross Lovegrove in1996 (Fiell & Fiell [1997] 2012, p.609);
2) *2-Legged pedestal chair*: Triennale chair, designed by Antti Nurmesniemi in 1960 (Feduchi [1946] 1986) and Santa chair, designed by Luigi Serafini in 1992 (Fiell & Fiell [1997] 2012, p.559);
3) *X-Legged chair*: Kreuzschwinger chair, designed by Till Behrens in 1983 (Fiell & Fiell [1997] 2012, p.504);
4) *Asymmetric chair*: B5 chair, designed by Stefan Wewerka in 1982 (Fiell & Fiell [1997] 2012, p.482) and Steltman chair, designed by Gerrit Rietveld in 1963 (Fiell & Fiell [1997] 2012, p.323).

Further existing chairs, that currently are not part of the sample, are specified in the appendix of the chapter **Multipurpose Chair Ontology**. The analysis of the sample was one of the major sources for the development of the ontology described in the next chapter.

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3.6 Appendixes

Multipurpose Chair Ontology

4

4 MULTIPURPOSE CHAIR ONTOLOGY

An ontology is an effective means of capturing the characteristics of the individuals of a product class, based on their similarities (shared by all individuals) and differences (specific to each individual). This chapter provides an ontological classification of multipurpose chairs. The main features described by the ontology address the chair parts and its types, its generic shape and overall dimensions. Other features concerning product knowledge (including function, aesthetics, symbology, materials, and construction) are also included, as well as features related to the generation process knowledge. The ontology was developed using the methods of literature review and artefact analysis. The main features of the computational ontology are systematically presented in schemas, descriptions and diagrams.

4.1 Introduction

This chapter refers to the third stage of the computational model specified in the **Introduction** chapter. The aim of the chapter is the study of form of a particular product class, in an epistemological and ontological approach. The selected class for this study is multipurpose chairs.

The study of form is a concern of several disciplines, originally related to biology but later associated to other domains, such as: morphology (the study of form and structure), morphometry (the measurement of form), and morphogenesis (the study of the development of form). These disciplines can be applied to the study of natural, artificial, or abstract forms. In the domain of chairs, there are two examples of systematic studies of form: a taxonomy of office chairs, which analysis and classifies 130 chairs according to the shape and the materials of their parts (Olivares 2011), and a morphological analysis of office chairs, based on the main shape of each part of the chair (Hsiao & Chen 1997). Beyond the analytic features, this last system also allows the generation of new solutions, through a combinatorial process.

The study of form can be formalized into computational ontologies. This formalism comprises the application of the philosophical concept of ontology to computational domains. Ontology is a branch of philosophy which deals with the study of being; the term is derived from the Greek *ontos* (being) and *logia* (the study of). The term is closely related to the philosophical meaning of the Latin term *form*, which derived from two Greek words: *morphe* (visible form) and *eidos* (conceptual form). It contemplates the dualities present in the pairs form/matter, abstract/concrete, and general/particular. Ontologies describe general, abstract forms that can be represented in several concrete particular instances. Computational ontologies were first introduced by Gruber (1993), as a formalism to provide an explicit conceptualization of a domain. Ontologies are knowledge-based systems that describe an abstract view of the world from a particular perspective, and are intended for knowledge sharing. These systems represent a domain by a taxonomic classification of entities, their properties and their relations. Ontologies must address the following criteria (Gruber 1995): clarity (the definitions of the terms must be objective, context-independent and complete); coherence (the vocabulary must be logically consistent); extendibility (the ontology must be extendable in such a way that new conceptualizations do not require the revision of existing ones); minimal encoding bias (the conceptualization must not address particular representation styles); and minimal ontological commitment (the ontology must make as few claims as possible). An example of an ontology applied to the chair domain is a data model which encodes chair design knowledge, by a diagrammatic representation of abstract entities and their relations (Eastman 1992). This model allows the representation of product properties, supports different abstraction levels, and is extendible to further conceptualizations.

The study of the form of multipurpose chairs, presented in this chapter, follows the formalism of computational ontologies. The goal of this study is to provide clear, coherent, and context-independent design knowledge. The ontology was developed according to the methods of artefact analysis and literature review (Martin & Hanington 2012). The former considered as a source the **Multipurpose Chair Sample** and the latter, a set of generalizations made by other authors. The form of multipurpose chairs is related to several features, addressing both product knowledge and design process knowledge. This ontology is divided into two main sections: the first addresses the features employed in the **Multipurpose Chair Grammar**, and the second addresses non-employed features. Each section includes the following universe of discourse:

1) *Section One*: parts (topology or structural relation between parts), geometry (including dimensions and shape), types and styles (related to classifications of chairs), and generation (addressing the addition sequence of parts);

2) *Section Two*: functions (primary, practical, aesthetic, and symbolic functions) and materials (related to materials, construction, and physical properties).

The ontology of *Section One* concerns three abstraction levels: the **Meta-Ontology** (a generic ontology, applicable to other kinds of furniture items or other kinds of products); the **Multipurpose Chair Ontology** (a specific ontology, applicable to the domain of multipurpose chairs); and the **Design Ontology** (an application ontology, applicable to instances, which in this case are individual chairs). The latter will be exemplified with the chair **214**.

The concepts, attributes and relations of *Section One* are represented in three different modes: (1) schemas (graphic-based visualization), providing a graphic representation of each concept (2) tables (text-based visualization), specifying the definition of each concept in Excel spreadsheets, and (3) diagrams (graph-based visualization), which illustrate concepts and their hierarchic relations, implemented in the software VUE – Visual Understanding Environment (Kumar & Kahle 2006). The concepts will be occasionally exemplified by chairs from the **Multipurpose Chair Sample** (cross-referenced in bold) and other chairs of the population.

As described in the **Introduction** chapter, the ontology comprised four versions. The version that will be discussed in this chapter is the last one (version 1.2). **Appendix 4.B.1** describes the main changes from version 1.1.

4.2 Domain Definition

This ontology addresses the domain of multipurpose chairs. The domain will be defined by a top-down approach, addressing two levels of domain decomposition: (1) seats – definition and types (which includes chairs); and (2) chairs – definition and types (which includes multipurpose chairs). The definition of the domains and their hierarchical relation is useful to validate the domain definition, by clarifying what a chair is and what a chair is not. A basic taxonomy of the seat class is illustrated in **Fig. 4.1**, and will be briefly described below.

Seats

A seat is a type of furniture. Furniture may defined as "movable pieces of functional equipment, usually found in a location with some degree of residential permanency"[1] (Encyclopædia Britannica [1768a] 1975, p.362). The function of furniture items is either to support the human body (e.g. chairs and beds), support objects (e.g. tables and desks), or contain objects (e.g. cabinets and wardrobes).

A seat is intended to support the human body in a sitting position. There are several types of seats, sharing the same primary function but comprising different features, such as:

1) *Chair*: a seat with a backrest, for individual usage and movable. A more detailed definition and some types of chairs will be described in the next section;
2) *Stool*: a seat without backrest, intended for a single user. There are different types of stools, such as: *barstools* (a tall seat with or without backrest; usually used together with a high table) and *footstools* (a low seat without backrest, used to support the feet);
3) *Bench*: a seat for multiple users, with or without backrest;
4) *Kneeling chair*: a forward tilted seat, with a knee support, with or without backrest;[2]
5) *Sofa*: an upholstered seat for multiple users (also called *couch*);
6) *Lounger*: a low seat with a long depth (which supports the legs horizontally), and with a backrest (also called *chaise lounge*);
7) *Bean bag:* a flexible seat without structure (like a cushion), adaptable to several sitting positions.

[1] "The English word comes from the French *fourniture*, which means equipment. In most other European languages, however, the corresponding word (German *möbel*; French *meuble*; Spanish *mueble*; Italian *mobile*) is derived from the Latin adjective *mobilis*, meaning movable" (Encyclopædia Britannica [1768a] 1975, p.781). Note that, although furniture is predominantly movable, it can also be built-in.

[2] Given its name, the kneeling chair should in principle be considered a type of chair, but this was not considered since it may not have a backrest.

Other types of seats include automobile seats, aircraft seats, and public seating (e.g. airport seats). Different types of seats require different shapes and dimensions in order to accommodate different sitting positions (e.g. longue chairs invite reclining positions, while dining chairs are suitable to upright postures). The types of seats are related to spatial-temporal contexts; for instance, the throne was characteristic of ancient eras but is practically unused nowadays, while office chairs became one of the most studied and used types in contemporary Western societies. The more recently developed seat types include the kneeling chair and saddle chair, which reflect the contemporary ergonomic concerns.

The characterization of the seating family is useful to test the definition of chair, by verifying what distinguishes chairs from similar objects. For instance, stools and footstools do not have a backrest, barstools and kneeling chairs may not comprise a backrest, benches and sofas accommodate more than one person, and automobile seats are not movable.

Chairs

A chair is a type of seat. The word *chair* comes from the Greek *kathedra* (meaning ‘to seat down’), which in turn is a combination of the words *kata* (‘down’) and *hedra* (‘to seat’). The term originated the Latin *cathedra* (‘seat’), conveying a meaning of authority (a bishop’s or a professor's seat). *Cathedra* derived into *cathedralis*, meaning the church of the bishop’s seat (Massey 2011). There are several definitions of the term *chair* available in literature, namely:

> *“[The chair] is a structure that holds your body above the ground in a seated position” (Massey 2011, p.8);*
>
> *“The chair must adequately support the weight of the sitter at such a height that the legs hang down and the feet touch the floor” (Fiell & Fiell 2002, p.5);*
>
> *“A chair, normally, is designed to support one person; it has a horizontal seat, supported above the floor by legs or some equivalent structure, and it provides support for the back” (Ashby & Johnson 2002, p.104);*
>
> *“A chair is a stool with a back-rest, and a stool is a board elevated from the ground or floor by supports” (Dresser [1873] 2013, p.53);*
>
> *“Chair: seat with a back, intended for one person” (Encyclopædia Britannica [1768b] 1975).* The same source mentions a broader definition*: “While most other forms [of furniture] (except the bed) are intended to support objects, the chair supports man. The term chair is used here in the wildest sense, from stool to throne to derivative forms such as the bench as sofa, which may be regarded as extended or connected chairs” (Encyclopædia Britannica [1768a] 1975, pp.785–6).*
>
> *“Chair: type of seat furniture for use by one person” (Turner 1996).*

Based on the previous definitions, the one adopted in this study is the following:

A chair is an object whose function is to support the human body in a sitting position; for individual usage and movable. In the sitting position, the thighs are supported by a nearly horizontal raised surface (seat), the back is supported by a nearly vertical surface (backrest), and the feet are supported by the floor.

There are chairs of many types; chairs for relaxing and chairs for working; chairs for adults and chairs for children; chairs for barbers and chairs for dentists; chairs to be born in (birth chairs) and chairs to die in (electric chairs). The chair class can be decomposed according to purpose, context, movement and user.

Purpose: chairs can be intended for various uses (multipurpose) or one specific use (single purpose):

1) *Multipurpose chair*: a chair that is suitable for several purposes. This type of chair can be used in several activities (such as resting, eating, working and waiting), unlike single purpose chairs, which are oriented for a specific use (e.g. office chairs and lounge chairs) or user (e.g. children's chairs). Furniture of general use is the one that is not intended for any specific operational context, such as domestic, religious, professional, or technical (Nunes 2012). The multipurpose chair was highly developed in the 1950s, when the smaller domestic interiors required flexible chairs, which could adapt to several uses and needs. The multipurpose chair is also called multiuse chair (Nunes 2012), general purpose chair (Pheasant [1986] 2003) and multifunctional chair (Design Museum 2009);

2) *Stacking chair*: a chair which is stackable (on other identical chairs) in order to reduce storage space; is usually a multipurpose chair. The chair **No. GF40/4**, designed by David Rowland in 1964 (Fiell & Fiell [1997] 2012, p.325), can stack 40 units in a height of 4 feet (1200 mm);

3) *Office chair*: a chair intended for an office context, including working, writing, and typing activities. These chairs typically have a 5-star base with casters, a swivel seat and an adjustable seat height;

4) *Easy chair*: a chair for relaxing, resting or reading purposes (also known as *armchair* or *lounge chair*). In relation to the multipurpose char dimensions, the seat height is lower, the seat width and depth are larger, and the seat and backrest tilt are bigger. The comfort is a main priority, thus it is frequently upholstered. It is typically used in a living room, and it is not suitable to be used with a table. A *wing chair* is an easy chair with protrusions on the sides of the backrest.

Context: chairs can be intended for particular environments, such as:

5) *Dining chair*: a chair intended to be used in dining rooms, together with a dining table. Typically it is a side chair (i.e., an armless chair) and has a higher backrest when compared to the multipurpose chair;

6) *Classroom chair* (also named *school chair*)*:* a chair intended to be used in a classroom, together with a desk or with an incorporated tablet (*tablet arm chair*). This type of chair needs to be particularly resistant and to address rigorous safety requirements;

7) *Outdoor chair* (also named *garden chair*): a chair intended for outdoor or exterior usage, as opposed to indoor chairs. Outdoor chairs must be resistant to weather conditions, thus they are usually waterproof and fireproof (e.g. **Omkstak** chair). Outdoor chairs include *lawn chairs* (an outdoor folding chair), *beach chairs,* and *terrace chairs* (e.g. **Gonçalo** chair);

8) *Deck chair:* is an outdoor folding chair for leisure purposes; originally it was used in cruise ship decks.

Movement: chairs can embrace different types of motion, considering different movements of the sitter. The motion may be given by the form of the chair (e.g. rocking chairs), by moving parts – which may be or not activated by mechanisms (e.g. swivel chairs and recliner chairs), by malleable materials (e.g. cantilever chairs) or by shock mounts (e.g. **DCW** chair). Moreover, chairs can be flattened for storage (e.g. folding chairs and inflatable chairs). Some types of chairs within this category are:

9) *Folding chair*: a portable chair that folds to be more easily transported or stored;

10) *Swivel chair:* a pedestal chair whose seat and back swivel in relation to a central axis;

11) *Recliner chair*: a chair whose seat and back tilt under the weight of the user;

12) *Rocking chair:* a chair with two curved pieces in the base, which allow the user to swing back and forth; usually intended for leisure activities;

13) *Hanging chair*: a chair suspended on the ceiling (thus not having any contact with the ground) or other kind of structure, allowing oscillatory or circular motions.

User: chairs can be intended for specific users, such as:

14) *Children's chair*: a chair intended for children, comprising smaller dimensions than the ones intended for adults;

15) *Child's high chair*: a chair used for feeding babies; the seat is higher than the one of the children's chair so that the child can be at the same level of the adult's table;

16) *Wheelchair*: a chair with wheels, intended for individuals with locomotion restrictions;

17) *Executive chair*: an office chair usually used by individuals of higher positions in an organization; in the same way as the throne is intended for magistrates. Executive chairs have a higher back and are usually more expensive than regular office chairs.

This ontology addresses the particular type of multipurpose chairs, for adult users. The domain also includes multipurpose stacking chairs and multipurpose outdoor chairs.

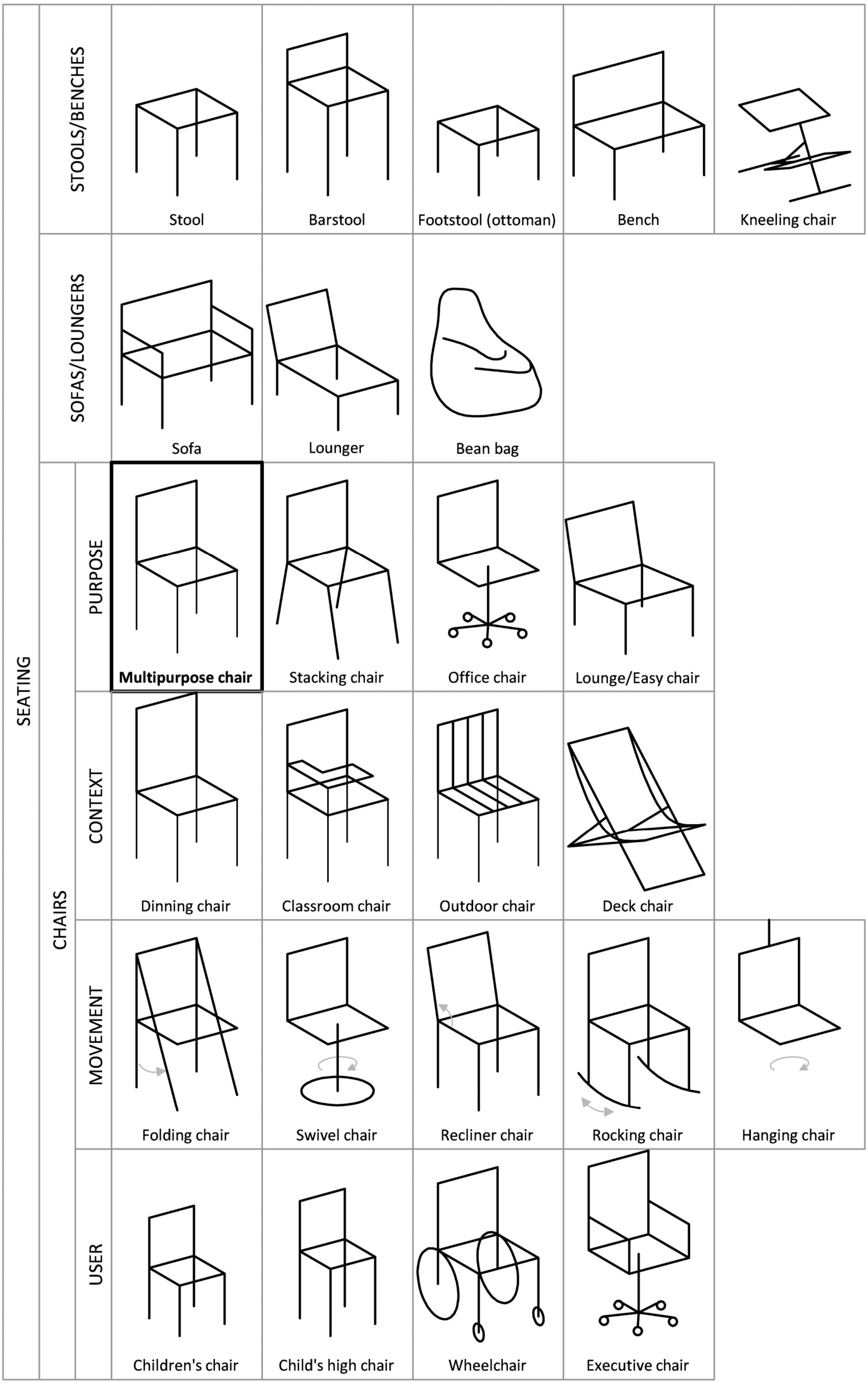


Fig. 4.1 Some types of seats

4.3 Section One

4.3.1 Parts

A design can be decomposed into several parts. According to Kilian (2006), there are two decomposition approaches: component-based (describing components) or functioned-based (describing functional areas). A match between functions and components is not guaranteed, since one component may contain several functional parts, and one functional part may contain several components. The approach adopted in this ontology is functional-based.

The chair is decomposable into parts; each having a specific function and location within the whole. There is no standard terminology of the parts of the chair; the same part can be described by different terms and the same term can be assigned to different parts. The terminology existing in literature is mainly related to woodworking domain (e.g., Hart 2017; Jackson, Day & Jennings [1989] 1996) or to the domain of furniture historical styles (e.g., Forrest 1996). As a consequence, the definitions are often restricted to four-legged wooden chairs.

The terminology used by this ontology is inspired by the traditional woodworking terms but addresses a more general abstraction level. This ontology comprises two levels of decomposition: groups of parts and parts. There are six groups of parts, corresponding to the main functional areas of the chair (**Fig. 4.2**):

1) *Legs*: nearly vertical part which supports the seat above the ground;
2) *Seat*: nearly horizontal part which supports a person's thighs while seated;
3) *Back*: nearly vertical part which supports a person's back while seated (also called backrest);
4) *Stretchers*: nearly horizontal part which joins and strengthens the legs;
5) *Base*: horizontal lowermost part which provides stability to the chair;
6) *Arms*: nearly vertical side part which supports a person's forearms while seated; also eases the stand-up/sit-down action.

There are three mandatory groups of parts – Legs, Seat, and Back, being the remaining three groups optional – Stretchers, Base, and Arms. The groups in direct contact with the human body are the Seat, the Back and the Arms (supporting, respectively, the thighs, the lumbar region of the back, and the forearms).[3]

[3] This ontology disregards parts that are not characteristic of multipurpose chairs, such as the headrest and footrest.

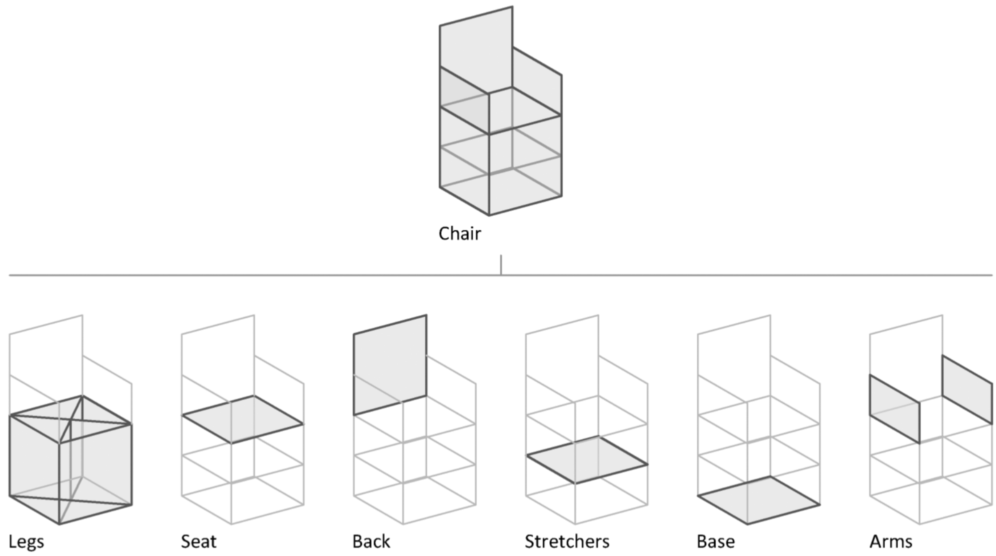


Fig. 4.2. Groups of parts of the chair

The groups of parts were decomposed into 39 parts, characterized by their position within the group. The parts can assume three main configurations (illustrated in **Fig. 4.3**):

1) *Guides*: bounding perimeter of a functional area, depicted by grey lines (note that guides are auxiliary grids and thus are not actually parts);

2) *Frame*: structural linear parts of the chair, depicted by double-thick black lines;

3) *Panels*: supporting planar parts of the chair, depicted by grey planes.

The parts can be visualized in two different modes (illustrated in **Fig. 4.3**):

1) *Wireframe mode*: represent the internal structural skeleton of the part;

2) *Solid mode*: represent the external form of the part.

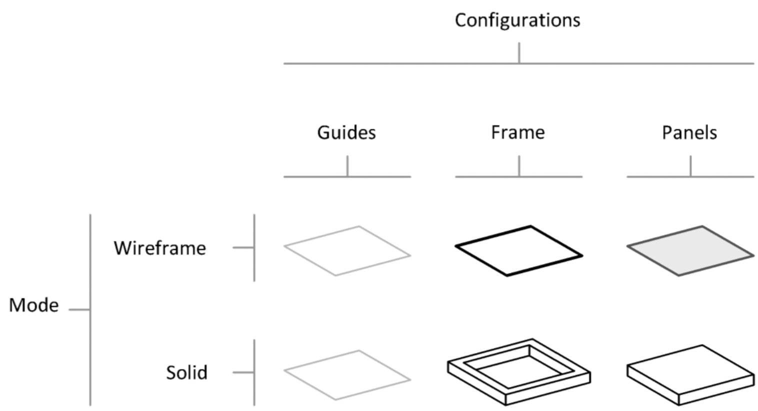


Fig. 4.3 Parts configurations

The parts of the chair are illustrated in **Fig. 4.4**. All groups of parts (except the Legs) are generically divided into: Outer Frame (composed by Front Rail, Back Rail and Side Rail) and Inner Frame (composed by Cross Rail, Long Rail and Radial Rail). The nomenclature of parts in the Seat, Stretchers and Base groups are analogous; for e.g.: Seat Front Rail, Seat Back Rail and Seat Side Rail (Outer Frame) and Seat Cross Rail, Seat Long Rail and Seat Radial Rail (Inner Frame). In the Back group, the parts names are, correspondingly: Bottom Rail, Top Rail and Upright (Outer Frame) and Cross Rail, Splat and Radial Rail (Inner Frame). In the Arms group, the parts names are, correspondingly: Front Support, Back Support, and Armrest (Outer Frame) and Side support (Inner Frame); the Arms group do not include Long and Radial rails.

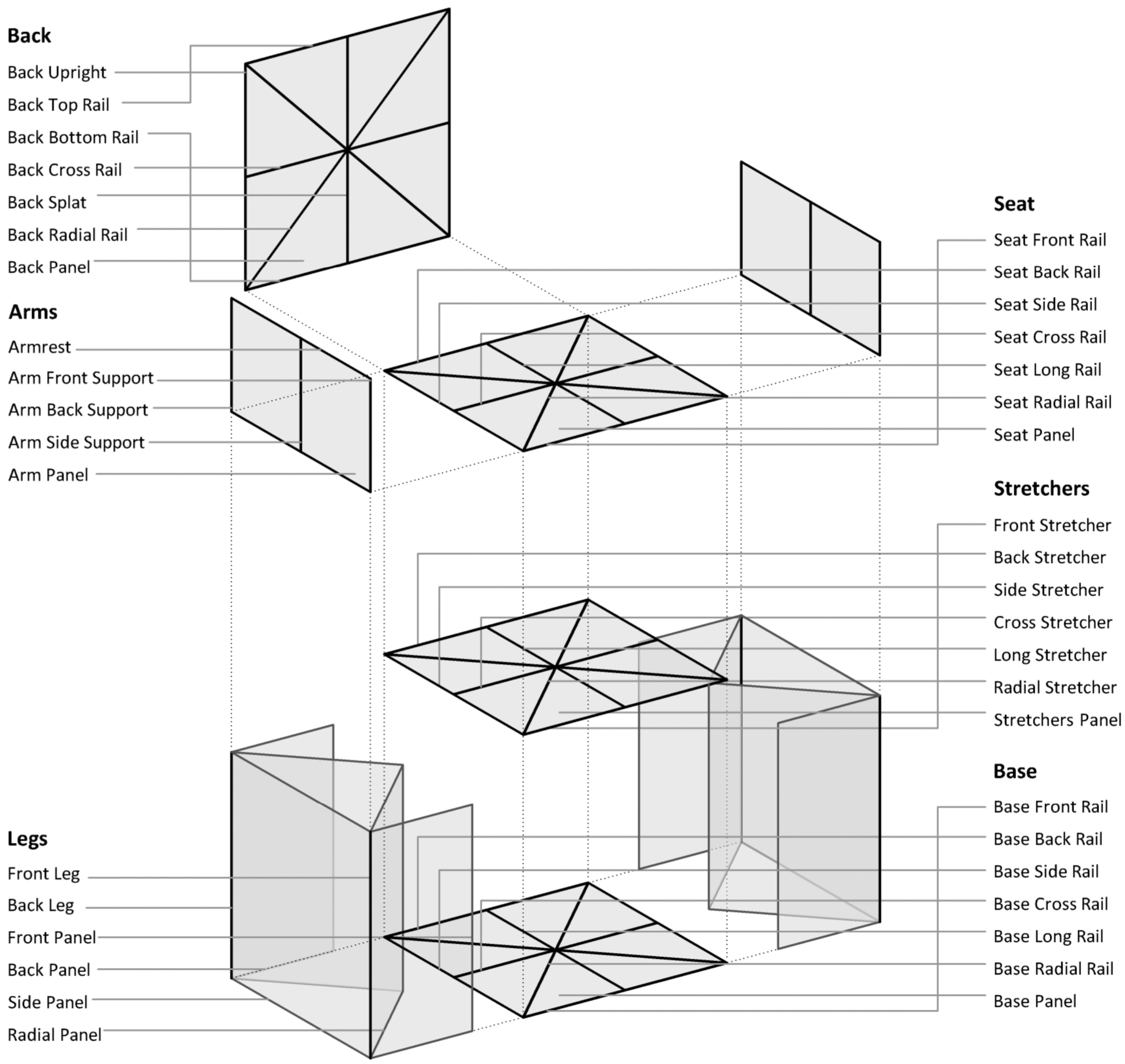


Fig. 4.4 Parts of the chair

This ontology of parts comprises an abstraction level, particularly in the Inner Frame parts. This group of parts only considers connections between two opposite Outer Frame parts. It disregards any other configurations, such as: (1) adjacent parts, i.e., Inner Frame parts aligned side-by-side to Outer Frame Parts; and (2) connections between adjacent sides of the Outer Frame.

The Meta-Ontology of parts is described in **Appendix 4.A.1** (table). The Multipurpose Chair Ontology of parts is detailed in **Appendix 4.B.1** (table), **Appendix 4.B.3** (schema) and **Appendix 4.B.5** (diagram). A Design Ontology of parts, regarding the chair **214**, is displayed in **Appendix 4.C.1** (diagram).

The diagram of the Design Ontology of parts shows the connection between the parts of the chair, which allows counting the number of components. In one extreme case, no parts are connected (e.g. **Superleggera** chair), while in other extreme case, all the parts are connected and the chair is constituted by a single piece (e.g. **Panton** chair), producing a visually harmonic whole. The connections between parts may be a trigger for innovation (Caniggia 1995). The components of the chair are a feature to be addressed in future work.

4.3.2 Geometry

Dimensions control positions, sizes and shapes of the chair parts. This ontology addresses different types of dimensions: linear, angular, and radial dimensions. There are absolute dimensions, expressed in millimetres and degrees, and relative dimensions, expressed in percentages. Each dimension corresponds to a parameter, which comprises a range (indicating a minimum and a maximum value) and a default value. The default values correspond to the mid value of the range, except in angles and radius (where the default is the minimum value) and in the sizes of the parts in the solid mode (where the default is 30 mm for the frame and 10 mm for the panels; based on the mean of the sizes of the sample chairs).

Anthropometric Dimensions

The primary function of the chair is to accommodate the human body in a sitting position; therefore shapes, dimensions, and proportions are closely related to the ones of humans. For instance, most chairs are bilaterally symmetrical, as the human body.

The anthropometric dimensions of the chair are the most important ones. Their adequacy to the human body is essential to ensure comfort and avoid health issues, such as spine curvature, back ache, and disk injures (Kroemer & Grandjean 1997). These are based on anthropometric measurements of the human body. Ergonomics considers anthropometrics to provide guidelines for the main dimensions of the chair; these guidelines are commonly used as a design tool. Ergonomics searches for the best interaction between the users and the products, considering criteria of comfort, safety and efficiency (Pheasant [1986] 2003).

The ergonomic recommendations vary, depending on the source. **Appendix 4.D.1** presents a comparative study between seven sources, addressing 21 dimensions recommended for adult chairs. Some sources are more complete than others, and some measures are redundant. The study includes: (1) recommendations for office chairs (Kroemer & Grandjean 1997); (2) recommendations for executive and office armless chairs (Panero & Zelnik [1979] 1998); (3) recommendations for chairs (Pheasant [1986] 2003); (4) recommendations for office chairs (Tilley & Henry Dreyfuss Associates [1993] 2002)[4]; (5) the European standard EN 1335-1 for office chairs (CEN 2000); (6) the North American standard ANSI/HFES 100 for office chairs (ANSI 2007); and (7) the North American ergonomic guideline BIFMA G1 for office chairs (BIFMA 2013).[5] This ontology addresses ten main chair dimensions (illustrated in **Fig. 4.5**, left):

1) *Seat Height*: is the vertical distance between the front edge of the Seat and the floor. It corresponds to the popliteal height; it should not be too high (otherwise the pressure in the back of the thighs increases and the circulation in the feet decreases) or too low (otherwise the hip joint is damaged, the natural curvature of the spine is reversed, and the stand-up/sit-down action is hindered);

2) *Seat Depth:* is the distance between the front and rear edges of the Seat. It corresponds to the buttock-popliteal length; it should not be too long (otherwise the back of the knees are pressured, the spine gets a poor support and the stand-up/sit-down action is hindered) or too short (otherwise the thighs support is decreased);

3) *Seat Width:* is the distance between the side edges of the Seat. It is related to the hip breadth; it should be large enough to accommodate one user;

4) *Seat Tilt Angle*: is the Seat angle measured from the horizontal. Most studies recommend the seat to be tilted backward to counteract the tendency of the buttocks to slide forward and increase the spine support; however some authors advocate a forward tilted seat to counteract the spine bending (Opsvik 2008);

5) *Back Height*: is the height of the upper edge of the Back above the Seat surface. There are three types of Back height (Pheasant [1986] 2003): lower-level (supports the lumbar and the lower thoracic region, releasing the arms); medium-level (supports the shoulder and the upper back); and high-level (supports the neck and the head);

6) *Back Height Spacing*: is the height of the gap between the seat surface and the lower edge of the backrest. The empty space in the lower Back is recommended to leave space for the buttocks and to prevent the pelvis to be pushed forward;

7) *Back-Seat Angle*: is the angle between the Back and Seat surfaces. It is recommended to be obtuse in order to reduce the intradiscal pressure and decrease the lumbar muscle

---

[4] The thickness of the seat and back pad and the radius of the borders curvature were not included.

[5] The standard EN 1335-1is used for chair certification in renowned European companies such as Cappellini and Vitra, while both ANSI/HFES 100 and BIFMA G1 are employed as a reference guide in renowned North American companies such as Knoll.

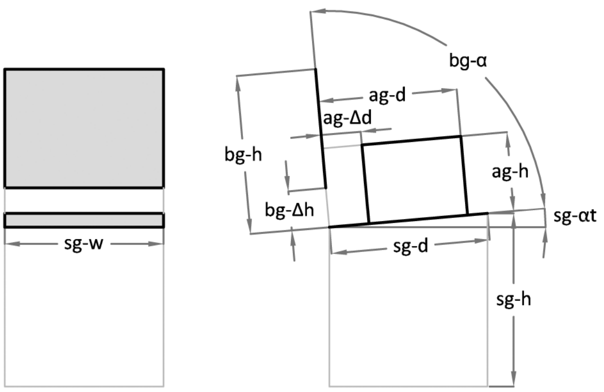
activity; however if the angle is exaggerated the buttocks are moved forward and the stand-up/sit-down action is hindered;

8) *Arms Height*: is the distance from the top of the Armrest to the Seat. It corresponds to the elbow height;

9) *Arms Depth*: is the distance between the front edge of the Armrest to the Back surface. It is intended to support the forearm;

10) *Arms Depth Spacing*: is the depth of the gap between the rear edge Armrest and the Back surface. It is intended to release the bony parts of the elbow.

The current version of the ontology includes 18 values, relative to maximum and minimum values of the dimensions. The values were mainly withdrawn from Tilley & Henry Dreyfuss Associates [1993] (2002), because it contains one of the most complete data, is a relatively recent source, and contemplates a wide range of users (98% of the study population) and of chairs (including the Seat Height of all the chairs of the sample). However, two values were retrieved from Pheasant [1986] (2003).[6] The values are presented in **Fig. 4.5**, right. The recommendations for the Arms Depth (maximum) and the Arms Depth Spacing (minimum) were not considered in this ontology, since they did not contemplate armrests with a depth equal to the one of the seat. Other anthropometric dimensions were not addressed, such as: Back Width, Back Horizontal Radius, Back Lumbar Height, Arms Width, and Arms Width Spacing.



Parameter	ID	Unit	Range	Default
Seat Width	sg-w	mm	[406,560]	483
Seat Depth	sg-d	mm	[406,508]	457
Seat Height	sg-h	mm	[368,480]	424
Seat Tilt Angle	sg-αt	°	[0,5]	0
Back Height	bg-h	mm	[330, 635]	483
Back Seat Angle	bg α	°	[90, 105]	90
Back Height Spacing	bg-Δh	mm	[0, 200]	0
Arms Height	ag-h	mm	[191, 254]	223
Arms Depth	ag-d	%	[0,100]*	100
Arms Depth Spacing	ag-Δd	mm	[0,100]	0

* 0% corresponds to 245mm and 100% to sg-d

Fig. 4.5 Anthropometric dimensions of the chair

[6] These values are: Back Height Spacing (max) and Arms Depth Spacing (max), which were not withdrawn from the main source because, in the former case, it did not accommodate 6 chairs of the sample, and in the latter case, no recommendation is provided.

The selection of the adequate anthropometric data must consider both the task and the user (CEN 2000). However, the choice of the most adequate data in a design process comprises several issues. Firstly, the type of product being designed may not match exactly the one analysed in the data. In this case, the majority of the recommendations address office chairs, although the present research is about multipurpose chairs.

Secondly, the target user of the product may not match the population of the anthropometric study. The study may be outdated or address data from a highly specific population (e.g. USA military sources). This is becoming less suitable as products are increasingly being developed for worldwide markets. Note that anthropometric measures should not be exactly mapped into the product; for e.g., the Seat Depth should have less 50 mm than the buttock-popliteal length (Molenbroek & Bruin 2005).

Thirdly, another aspect to take into consideration is the percentage of population contemplated in the study. Almost all the aforementioned sources accommodate approximately 90% of the population, considering persons bigger than 5th percentile female and smaller than 95th percentile male. This includes, for instance, people between 151 and 192 cm of body height (CEN 2000). Only source 4) accommodates approximately 98% of the population (considering 1th and 99th percentiles), an approach also employed by some renowned companies as Herman Miller (Stumpf, Chadwick & Dowell 2007).[7]

Fourthly, there is the issue of human variability. The human body comprises a great variety of sizes and shapes; beyond the uniqueness of each individual, there are variations relating to age (intra-individual), gender and ethnic group (inter-individual) and generation (secular variability) (Tilley & Henry Dreyfuss Associates [1993] 2002). Chair design may employ different strategies to contemplate this variety (schematized in **Fig. 4.6**):

1) *Design for the tall/small*: design a product for a significant majority of the population, addressing either the small people (5th percentile) or the tall people (95th percentile). In the case of chair design, this strategy is suitable for Seat Width, as by accommodating users with the largest percentile, the chair will also accommodate the smaller ones. However, this strategy is no longer applicable in other dimensions of the chair, such as the Seat Height. Another problem of this approach is that usually individuals do not have all the dimensions corresponding to the same percentile; for e.g., a person with a 95th percentile total height may not have a 95th popliteal height (Pheasant [1986] 2003).

[7] This study conducted by Herman Miller demonstrated that one-third of a sample of 778 participants had one of the four most crucial measures out of the range of 5th-95th percentiles.

2) *Design for the mean*: design a product for the average person (50th percentile). This strategy is commonly employed in non-adjustable multipurpose chairs, since for e.g. the Seat Height cannot be too high or too low.[8]

3) *Design for more types*: design a product in different sizes. For instance, the **Aeron** chair (Fiell & Fiell [1997] 2012, p.551) is available in small, medium and large sizes. This is a common practice in children's chairs, since they must contemplate a wide range of body dimensions.

4) *Design for adjustability*: design a product with adjustable positions (considering continuous or discrete ranges). The positions may either be changed by the user or be automatically adjusted to the user. This is a common strategy in office chairs (e.g. **Aeron** chair);

5) *Design for all*: design a product that is suitable for any individual. This is possible if the chair is designed for a specific user, which is not conceivable with mass production, but can be achieved with a one-off production or with mass customization.

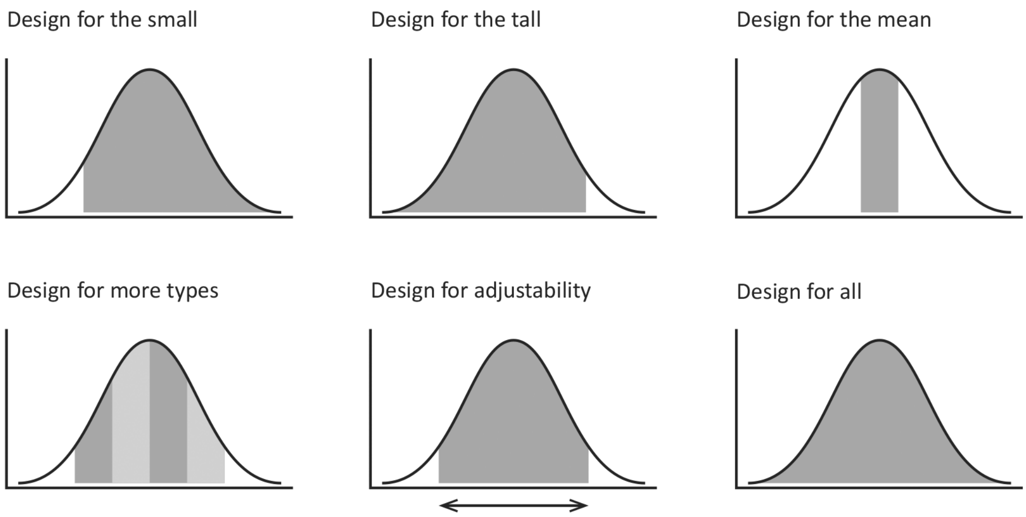


Fig. 4.6 Anthropometric Design Types (adapted from Molenbroek & Bruin 2005)

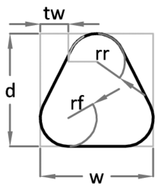
[8] This is verifiable in the **Multipurpose Chair Sample**. Approximately 50% of the chairs have a Seat Height in the range 440-460 mm, which is in the middle of the recommended range of 400-510 mm (CEN 2000).

Shape

The shape of the chair is controlled parametrically, i.e., different configurations can be obtained by changing specified dimensions. An example is given in **Fig. 4.7**, which illustrates the parametric shape of the Outer Frame, applicable to Seat, Back, Stretchers, Base and Arms. The shape is controlled by five parameters: Width, Depth, Front Radius, Rear Radius and Taper Width. By changing those parameters, one can obtain a square, a rectangle, a trapezoid, a triangle, a semicircle, a circle, a rounded rectangle, and a drop-shape, beyond other shapes.

Parameter	ID	Unit	Range	Default
Width	w	%	[1,100]	100
Depth	d	%	[1,100]	100
Front Radius	rf	%	[0,100]	0
Rear Radius	rr	%	[0,100]	0
Taper Width	tw	%	[0,100]	0

Outer Frame parameters



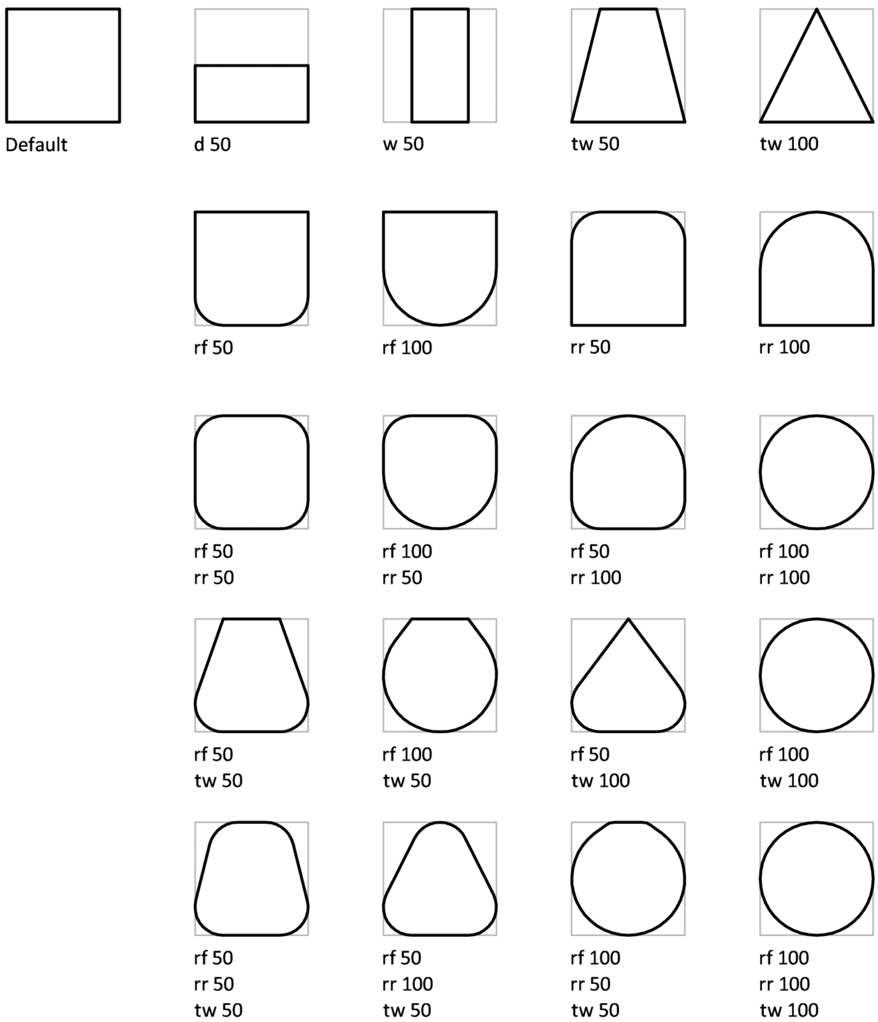
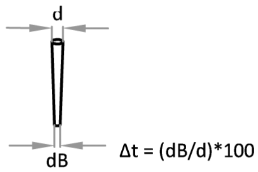


Fig. 4.7 Parametric shape of the outer frame

Another example is the parametric shape of the frame, illustrated in **Fig. 4.8**. The section can be either round or square. The size of the round section is given by the Diameter, and the size of the square section is given by Width and Depth. The tapered shape is controlled by the Taper Ratio parameter.

Parameter	ID	Unit	Range	Default
Diameter	d	mm	[1,280]	30
Width/depth	w/d	mm	[1,280]	30
Taper Ratio	Δt	%	[1,100]	100
Round/square Section	s	N/A	{r,s}	r

Solid Frame parameters



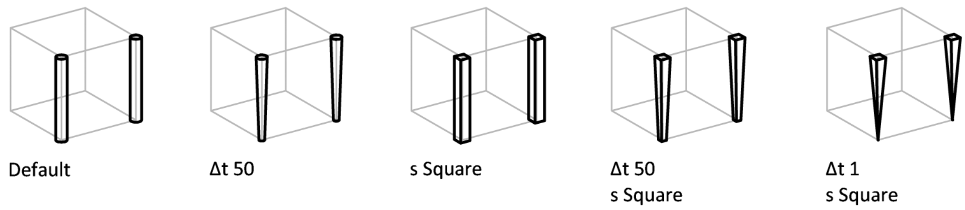


Fig. 4.8 Parametric shape of the frame

This ontology considers a high abstraction level of the shape, characterized by the following four rules:

1) The curves are simplified to lines and arcs; the latter ones can only be found in the corners of the outer frame and panels (excluding Legs);
2) The parts have constant thickness (except Legs that may be tapered);
3) The section shape of the frame can either be round or square;
4) The shape of the outer frame and panels (excluding Legs) can be circular, square, trapezoid, or assume intermediate shapes.

Future work will address the Seat and Back curvatures, considering the S-shape of the human spine. A study conducted by Kroemer & Grandjean (1997) provides a suggestion for the seat profile of multipurpose chairs, which was considered by a group of users as the most comfortable. Another important curvature is the one of the front edge of the seat, that is usually bent inwards to avoid injures in the popliteal region (Cranz [1998] 2000).

The ontology addresses other dimensions: position and number of the inner frame elements, position of the Legs, and position of the Stretchers. All the dimensions are illustrated and described in appendixes. The Meta-Ontology of geometry is described in **Appendix 4.A.2** (table**),** and in **Appendix 4.A.4** (schemas). The Multipurpose Chair Ontology of geometry is given in **Appendix 4.B.1** (table), together with the ontology of parts. The parameters will be described in detail in the next chapter (**Multipurpose Chair Grammar**).

4.3.3 Types and Styles

Both types and styles group objects that share similar features, but while the first is context-independent, the second is context-dependent. Types characterize function or morphology, while styles characterize periods, places or people.

Types

Types are context-independent classifications. Design types may group designs according to functions, materials, morphologies, or shapes (Ahmad & Chase 2012). As mentioned earlier in section **4.2**, chairs can be categorized according to their function (e.g. office chair, folding chair, and children's chair). Chairs can also be classified by materials (e.g. wooden chair and tubular steel chair); a characterization that will be later addressed in section **4.4.2**. This section comprises chair types which address morphology (e.g. cantilever chair) and shape (e.g. S-shaped chair) classifications.

There are two paradigmatic examples in literature of systematic classifications of chairs, both addressing the main parts of the chair. The first one (Nye 1900) presents a classification of chairs by their basic shape (disregarding ornamentation), based on the analysis of existing chairs of different styles. The chair parts are classified as following: Legs (straight, inclined, or crossed) and Arms (horizontal or sloping) are classified according to their side and front views; Seat (square, trapezoid, triangle, circle, or composite) and Stretchers (box, H-shaped, or X-shaped) are classified by their plans; and Back is classified by the outline shape (rectangular, trapezoidal, polygonal, elliptical, semi-circular, or shield) and composition (panelled, vertical, horizontal, or composite). The second one (Olivares 2011) consists in an extensive taxonomic classification of office chairs; this classification is more technical than the former and relate mostly to the parts connections and to the materials.

This ontology provides a generic classification of multipurpose chairs, given by the following three categories:

1) *Outer shape*: is the shape of the outline, which can be: square, circular, semicircular or trapezoid;
2) *Topological shape*: is the shape that the parts make with each other, which can be: none (if there are no parts), single, parallel, mesh, X-shaped, H-shaped, U-shaped, star-shaped, box-shaped, and solid;
3) *Number/position*: is the number of parts (one to four) and their position (front, back, or centre).

This generic classification is employed to classify the specific parts of the chair. The classification is divided into types (the ones that were considered as a selection criteria in the Iconic group of the **Multipurpose Chair Sample**) and subtypes. Thirty types were considered, schematized in **Fig. 4.9** and described below:

1) *Legs*: are classified by the number: 1-legged, 2-legged, 3-legged, and 4-legged. In order to avoid ambiguities, the number is counted underneath the seat, and considers agglomerates of legs as a single leg (e.g. the **Swag Leg** chair is 1-legged). Chairs with more than four legs (not agglomerated at the seat level) are uncommon, since they are functionally unnecessary. Subtypes address the legs positioning: 1-legged chairs can have one leg at the centre (pedestal), at the front (cantilever) or at the back (reverse cantilever); 2-legged chairs can have no back legs (cantilever) or no front legs (reverse cantilever), and 3-legged chairs can have two legs in the front and one in the back, or two legs in the back and one in the front. In cantilever chairs the frame is sustained by the tension of the material. Other subtypes consider leg agglomerates (e.g. double 4-legged chair). Legs can be further classified by the topological shape (X-shaped legs and solid-shaped legs), by the angle (angled legs), by the section shape (round, square and tapered legs), and by the curvature (although this type was not considered in this ontology);
2) *Seat*: is classified by the outer shape, which can be: square, circular, semicircular or trapezoid. The Seat can be further classified by the topological shape of the seat frame;
3) *Back*: is classified by the arrangement of the inner frame elements: ladder-back (horizontal elements), splat (vertical elements), mesh (horizontal and vertical elements), X-shaped, open (no inner elements), and solid (the Back is a continuous surface). The Back can be further classified by the outer shape and by its height;
4) *Stretchers*: are classified by the topological shape of the parts: single, parallel, X-shaped, H-shaped, U-shaped, and box-shaped. The Stretchers can be further classified by the outer shape and by combinations of configurations (e.g. box with U-shaped);
5) *Base*: is classified by the topological shape of the parts, which can be parallel (sled), X-shaped, U-shaped, star-shaped, box-shaped or solid. The Base can be also classified by the outer shape;
6) *Arms*: are classified by the number: the chair can have no armrests (armless chair) or two armrests (armchair). The case of a single armrest was not considered, as this ontology only addresses bilaterally symmetric chairs. Arms can be also classified by the outer shape and the topological shape.

New types can be achieved by combinations of the aforementioned types (e.g., the **Ply** chair has a box-crossed seat frame), or by a systematization of possibilities (e.g. the Legs types may be given by a connection between n points in the Seat plane and n points in the Base plane, although many combinations are not possible, due to stability restrictions).

The Meta-Ontology of types can be consulted in **Appendix 4.A.3** (table) and **Appendix 4.A.5** (schemas). The Multipurpose Chair Ontology of types is detailed in **Appendix 4.B.2** (table), in **Appendix 4.B.4** (schemas) and in **Appendix 4.B.6** (diagram). A Designs Ontology of types, regarding the chair **214**, is illustrated in **Appendix 4.C.2** (diagram).

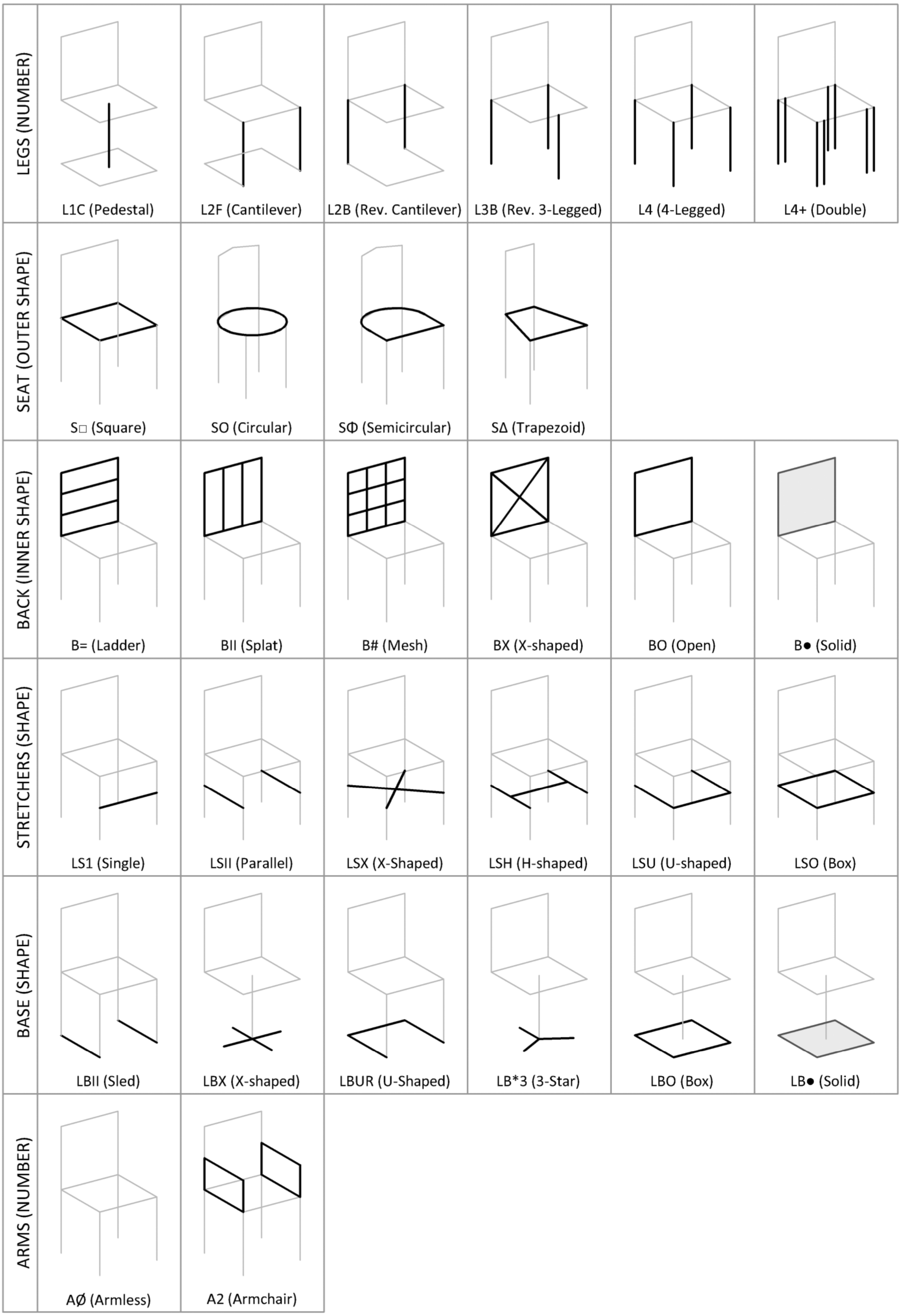


Fig. 4.9 Main chair types

Styles

Styles are context-dependent classifications. According to Chan (2000), design styles may group designs according to a period (period style), a place (regional style), a person (individual styles) or groups of persons (group style). Some styles may combine more than one of these categories, such as artistic movements. A design style reveals distinctive features observable in a set of designs, such as shape, structure, materials, techniques, and aesthetics. Some examples of design styles are described below:

Period styles: the history of the chair can be described through historical styles. The 18th century in France and in England is considered the golden age of the chair, with the proliferation of various iconic furniture styles. These styles were characterized by luxury and comfort, rich decoration and artistic work. They are named after the reigns: in France, *Louis XIV* (1638-1715), *Louis XV* (1722-1774), and *Louis XVI* (1774-1793); and in England, *Queen Anne* (1702-1714) and *Georgian* (1714-1830) styles. In the 19th century, styles also adopted period's names: the English *Victorian* style (1837–1901), and the French *Empire* style (1800-1815).

Regional styles: Modern design styles are often subdivided according to a specific region, such as: *Italian Design* (characterized by an emphasis in aesthetics and symbolic aspects, e.g. **Superleggera** chair) and *Scandinavian Design* (characterized by organic forms, natural materials, and functionalism, e.g. **Wishbone** chair).

Individual styles: in the 18th century, English furniture styles adopted the names of the most three prominent cabinetmakers, which combined the crafts of turner, carver and upholsterer: *Chippendale* (1718-1779), *Hepplewhite* (died 1786) and *Sheraton* (1751-1806). In the 19th century, cabinetmakers explored new methods of bending wood and with it new design languages, such as Samuel Gragg (1772-1855) and Michael Thonet (1796-1871). The Thonet style may be regarded a *group style*, as it refers to a family business.

Artistic movements: from the mid-19th century several art and design movements (characterized by distinctive features) have arisen, such as: *Arts and Crafts* (craft-produced products with simple and functional forms); *Art Noveau* (combination of aesthetic and rational aspects); *De Stijl* (abstract basic shapes and colours; e.g. **Zig-Zag** chair); *Bauhaus* (integrity of materials and manufacturing processes, rational forms, and affordable products); *Art Deco* (luxurious and superfluous decoration and materials, and design for elite); *Mid-Century Modern* (simple and organic forms; e.g. **DCW** chair), *Pop Art* (use of bright colours, original and extravagant shapes, and cheap materials; e.g. **Panton** chair); and *Postmodernism* (emphasis in symbolic, metaphoric and aesthetic aspects, and use of revivalisms and eclecticisms; e.g. **Queen Anne** chair).

The styles further explored in this research address two individual styles (of two different designers) and one group style (the *Thonet* style). The styles will be described in the chapter **The ChairDNA Design Tool**, through the characterization of a set of parameters that constrain the form.

4.3.4 Generation

In previous sections, the chair was analysed by its final form. This section addresses the generation of the form of the chair, considering all the intermediate steps from the initial to the final form of a particular design. The analysis of the evolution of the form of the chair, from a historical perspective, will not be addressed in this ontology.

Different form generation processes are observable in diverse activities, such as sketching, designing, modelling and manufacturing. The final form may be known *a priori*, for instance in industrial manufacturing processes, unlike in a design process. This ontology briefly addresses the form generation in design domains.

The description of the design process is a difficult task, since it relies on complex, inaccurate and ambiguous information, subjective to a particular designer and to a particular project. The form generation is constrained by several factors: the design phase (research, concept, development, detail, and production), the design tools (drawing, diagrams, models, CAD software, brainstorming, and others), the design task (ideation, 2D drawing, 3D modelling, etc.), and the design goals and constraints (assembly, cost, distribution, ergonomics, aesthetics, function, maintenance, materials, production, symbology, standards, sustainability, and user, among others).

In chair design, there are three cases describing design constraints, design tools, and manufacturing techniques used in the design process: (1) the first case analyses the design process of the *Myto* chair, designed by Konstantin Grcic in 2008 (Design Museum 2010). The study describes the constraints (materials and manufacturing techniques imposed by the client; the chair type and the cost imposed by the designer), and the tools used in the process (such as digital simulation and physical modelling). (2) The second case addresses the redesign process of three chairs (Szita 2012), including the *107* chair, designed by Robert Stadler in 2011. The chair was a redesign of the **214** chair, taking into consideration construction constraints (to be machine-produced and thus more affordable) and aesthetic constraints (to simplify the forms). (3) The third case documents a design exercise given to architecture students (Gier 2011). The task was to design several multipurpose chairs in different materials, and to build full-scale prototypes.

Although design constraints play an important role in the shape of a design (these will be later addressed in section **4.4.1**), these studies do not report an in-depth form generation process. One sparse example of the description of the generation sequence of a design is illustrated in **Fig. 4.10**. It depicts a subdivision process used in the design of the *Bone* chair (JDS Architects 2011).

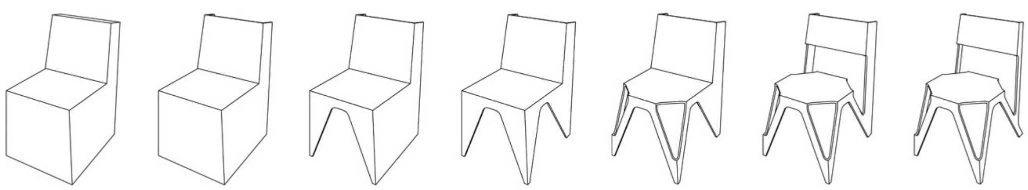


Fig. 4.10 Generation sequence of the Bone chair (JDS Architects 2011)

In the chapter **User Evaluation of ChairDNA,** the form generation process of ten chairs is analysed, according to the following characteristics:

1) *Shaping process*: the process can be additive, subtractive or formative, respectively comprising the addition, removal or transformation of elements. These terms are commonly employed to classify manufacturing processes (Thompson 2007), such as 3D printing, milling, and modelling, respectively. Other processes could be included, such as the ‘single gesture’ process inherent to freehand sketching.

2) *Method*: distinct design methods were described by Broadbent [1973] (1988): pragmatic (use of available construction methods), iconic (adaptation of existing solutions), canonic (use of rules such as grids or proportion systems), and analogical (use of analogies such as natural shapes). One can add the exploratory and analytic methods, among others.

3) *Inspirations and influences*: the design process is frequently derived from existing designs, design types, design styles, natural and artificial forms, and so forth. Analogies are very common in design, since “the designer does not approach each design problem afresh with a *tabula rasa*” (Lawson [1980] 2005, p.159).

4) *Strategy*: the generation can follow a decomposition top-down strategy from the general to the specific (i.e., from whole to parts), a composition bottom-up strategy from the specific to the general (i.e., from parts to whole), or use both iteratively. Although the design process is usually described with increasing levels of detail, there are cases where designers start with detail and proceed to the general shape.

5) *Use of grids/guides*: the designer can use, or not, construction lines as an underlying guidance for form generation.

6) *Environment:* the support of form generation may be physical or digital. The process can be predominantly developed in one of them, can move from one to another, or can use both iteratively. It can be processed in 2D or 3D space.

7) *Number of alternatives*: the process may consider one evolutionary solution or several intermediate solutions. The designer can proceed from one to several alternative solutions (divergent) or *vice versa* (convergent), although typically both are used. For instance, the designer generates several alternatives and then eliminates solutions and/or combines characteristics of several solutions. Note that the final solution may comprise different alternative configurations or a design collection. The process may also be classified into linear (the development of one idea at a time) and parallel (the development of various alternatives simultaneously).

8) *Generation sequence*: in an additive fragmented generation process, the order by which the parts of a design are generated can be analysed.

This ontology only details the additive fragmented process. A generation sequence for the **Parts** of multipurpose chairs is proposed, based on the analysis of the chairs of the sample. **Appendix 4.B.1** describes, for each part, the antecedent parts. The generation (decision tree) diagram is illustrated in **Appendix 4.B.7**.

4.4 Section Two

4.4.1 Functions

Product functions are related to the usages or purposes of a product that are mainly determined by design constraints. Constraints may be given by the various stakeholders in design (client, designer, engineer, manufacturer, supplier, distributor, seller, customer, user, legislator, etc.). Depending on the perspective, constraints restrict or drive the design exploration (Kilian 2006). Guiding principles are prominent constraints or goals imposed by the designer, based on his/her motivations, beliefs and values, instead of an accurate analysis of the problem; they are used to decrease the solution space and guide the decision-making heuristic process. Note that some design goals may not be achieved (for e.g., the **Tulip** chair failed to be a one-piece design).

Product functions can be classified into primary (mandatory) and secondary (optional). Bürdek (2005) also distinguishes between practical functions (related to technical performance and construction, e.g.: materials and manufacturing processes), and communicative functions (related to the interaction between users and objects). The latter category includes formal aesthetic functions (related to the visual appearance, e.g.: structure and shape), and symbolic functions (related to meaning or semantics, e.g. power). A similar classification was employed by Lawson [1980] (2005) to address the main types of constraints (radical or primary, practical, formal and symbolic). This last classification is adopted to succinctly describe the main functions of the chair.

Primary Function

The primary or basic function of the chair is to support the human body in a sitting position. In sitting positions, the body weight is mainly supported by the buttocks and the thighs (that rest on the floor or on a raised surface), being the trunk more or less upright. In a chair-sitting posture (Hewes 1955), the thighs are supported on a raised surface and the trunk is supported by a nearly vertical surface:

> *"The sole of the foot is placed on the floor; the foot forms an angle of approximately 90° with the lower leg; the lower leg is approximately vertical; the lower leg forms an angle of approximately 90° with the thigh; the thigh is almost horizontal; the thigh forms an angle of approximately 90° with the trunk;[and] the trunk is erect." (CEN 2000)*

The three most common chair-sitting positions – upright, forward leaning, and reclined (Dowell, Stumpf & Walker 2003), are illustrated in **Fig. 4.11**. The positions are characterized by the posture of the trunk and are related to the task: the upright position is usually accompanied by a table in activities such as eating, writing and working; the forward leaning position is commonly employed in tasks performed with a computer; and the reclined position is typically used in more relaxed activities. There are several other postures beyond these three main ones, characterized by the position of the legs – e.g., legs-together or crossed-legs position (Hewes 1955), or by more unconventional body positions, such as astride or backwards sitting positions (Design Museum 2009).

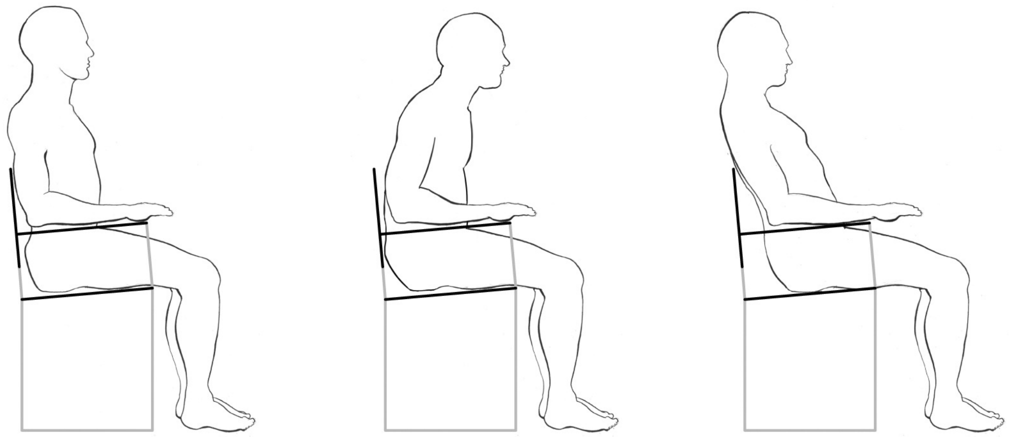


Fig. 4.11 Typical seated postures: upright, forward leaning, and reclining (from left to right)

In order to successively perform the primary function of supporting the human body, the chair must comprise other mandatory functions. The purpose of sitting is to (1) provide postural stability, (2) be comfortable for a long period of time, (3) be psychologically satisfactory and (4) be adequate to the designated task (Pheasant [1986] 2003). In order to bear the weight of the user without breaking or falling over, the chair must be resistant and stable (Design Museum 2010). The chair must also be easily moveable.

Comfort may be considered a primary function, although occasionally a high level of comfort is not recommended (e.g. in café chairs). Comfort is “a state of mind which results from the absence of unpleasant bodily sensations" (Pheasant [1986] 2003, p.60). The sitting comfort depends on the characteristics of the user, the object, and the task. Some measurements concerning comfort provide a set of ergonomic recommendations for chair design:

1) *Pressure on the sitting surface*: is measurable by pressure mapping systems. In the sitting position, 75% of the body weight is supported by the two bony prominences of the pelvis, called ischial tuberosities (Panero & Zelnik [1979] 1998). The higher the pressure, the greater the user discomfort and fatigue. The distribution of the load that the body exerts in the sitting surfaces may be enhanced by using upholstery, by rounding the surfaces edges of the seat, or by using voids;

2) *Pressure on the intervertebral discs and muscle activity*: in a sitting posture, the pressure in the intervertebral discs is 30 times greater than in the standing posture (Cranz [1998] 2000). The disk pressure is decreased when the back-seat angle is higher, and

when an adequate lumbar support to the back is provided (Kroemer & Grandjean 1997);

3) *Observation of the user kinematics*: the sitting position is not static; the deterioration of the bloodstream leads the sitter to change position about every 10 or 15 minutes (Fiell & Fiell [1997] 2012). The level of discomfort may be measured by the frequency that the user changes position, although this may be arguable, since the movement is conditioned by age, genetics, daytime or surrounding environment (Cranz [1998] 2000). Chairs that ease postural change (e.g. cantilever chairs) bring several health benefits.

4) *Body surface temperature*: the chair should be 'breathable', i.e., allow the dispersion of heat and humidity away from the body. The more neutral the sitting temperature, the more comfortable the chair. That requires a choice of breathable materials, as wicker or rattan (Béhar et al. 2013).

5) *Interviews/questionnaires and physiological analysis*: comfort depends on physiological factors and on the subjective perception of each individual. It deals with emotions, sensations, and taste, which, although subjective, are likely to be measured (e.g. by eye tracking and facial expression capture). Cognitive comfort is influenced by aesthetic (colour, texture, shape) and symbolic features, among others.

For ages, chairs introduced features directed to improve comfort, such as upholstered pads (e.g. **Tulip** chair), curved surfaces (e.g. **DCW** chair), or adjustable components. The most comfortable chair, according to the *New York Times* in 1974, was the *Karuselli* chair, designed by Yrjö Kukkapuro in 1964 (Sibthorp & Quin 2012, p.157). However, despite all the efforts to design the most comfortable chair, ultimately there is no optimal solution, since "all seats are uncomfortable in the long run" (Pheasant [1986] 2003, p.68). To be sitting in a chair for long periods of time is the cause of many health problems, such as backache, intervertebral disk injuries, blood circulation problems, joints and ligaments problems, digestive problems, fatigue, and stress (Kroemer & Grandjean 1997). The sedentary life of the 21th century is exacerbating this problem, since people spend on average five hours a day sitting (Bauman et al. 2011).

> *"Since the chair has been with us for at least ten thousand years, and its basic form has stayed more or less the same ever since, it may be thought to be perfect. (...) In actual fact, the chair is far from perfect, functionally speaking." (Cranz [1998] 2000, p.66)*

Some groundbreaking proposals aimed to revolutionize the form of the chair in order to improve comfort. Mandal (1981) suggested a perch posture (an intermediate posture between sitting and standing), obtained by the rise of the seat and working surface. The kneeling chair (Opsvik 2008), previously described, induces an obtuse angle between the spine and the legs, and a weight distribution between the buttocks and the knees. Although it is claimed to increase comfort, it is also argued that it adds extra load in knees and lower legs (Kroemer & Grandjean 1997).

Practical Functions

Practical functions are related to technical features, such as assembly, maintenance, cost, ergonomics, materials, production, sustainability, and user (Pahl et al. [1984] 2007). Chair design considers a wide range of practical functions, such as: stackable (e.g. **Omkstak** chair), outdoor use (e.g. **Landi** chair), modular (e.g. **Universale** chair), linkable (e.g. **Air** chair), lightweight (e.g. **Superleggera** chair), low-cost (e.g. **Polyside** chair), easily disassembled (e.g. **214** chair), easy to clean (e.g. **Polyside** chair), ecological (e.g. **Wiggle** chair), mass producible (e.g. **Omkstak** chair), made of recycled materials (e.g. **RCP2** chair), one-piece chair (e.g. **Bofinger** chair), and intended for a young market (e.g. **Universale** chair).

Formal Aesthetic Functions

Aesthetics is related to the perception of beauty, which may be regarded as something arbitrary and intrinsic to human judgment (Kant) or as a property of the object itself (Plato and Aristotle). The latter approach considers concepts such as proportion, harmony, symmetry, balance, and order. Elam (2001) claims that golden proportions, which are believed to be cognitive preferable, are present in many successful Modern chairs. For example, the author argues that golden rectangles and ellipses are observable in the **Tulip** chair (illustrated in **Fig. 4.12**, left).

Formal aesthetic functions comprise features such as structure, shape, dimensions, proportions, texture, and colours. The qualities of form are often characterized by pairs of opposites, such as organic (fluid and sensual curves) and geometric (right angles, and basic and symmetric shapes), solid and void, light and heavy, simple and complex, decorative and functional, continuous and discontinuous, and rough and smooth. Chairs may be classified according to their aesthetics; George Nelson mentioned three main styles of Modern chairs (Fiell & Fiell [1993] 1994): artisanal style (characterized by vernacular forms, not necessarily craft made, e.g. **Wishbone** chair), mechanic style (characterized by mechanical aesthetics, e.g. **Polyprop** chair), and biomorphic style (characterized by biological organic forms, e.g. **Tulip** chair).

In some cases, aesthetic functions may surpass functional aspects. Decorative functions were particularly emphasised in the chairs of the 18th century, as discussed earlier. In the extreme case, the chair can have a purely decorative function, when exhibited in museums as an artwork.

Symbolic Functions

Symbols refer to something beyond the object itself, and their interpretation is always dependent on a given individual in a certain socio-cultural context (Bürdek 2005). The chair frequently communicates symbols, messages or analogies, conveyed by its shape, materials or dimensions.

The primary function of the chair, until the 19th century, was symbolic: the chair was mainly used by monarchs and leaders as a symbol of authority. The ability to assign power was given by the rise of the sitter (in relation to those who sit on the floor), by the individual usage, by the backrest (which directs the sitter into its audience), and by the armrests (which reduce proximity). This function persists nowadays in the executive chairs intended for the employers, as opposed to chairs used by employees. The higher the backrest and the richer the materials and decorations, the greater the social status of the sitter.

The chair is rich in analogies. The anthropomorphic analogy is given by the close relation of the chair to the human body, as expressed in terminology of its parts (legs, back, arms, feet, and ears). Moreover, the chair can express identity, reflecting the personality of its user (in the same way as clothes) or of its creator, as the case of the painting *Van Gogh's Chair* (Design Museum 2010). Chairs are more often associated to the designer (e.g. **Panton** chair) than to the brand, unlike designs in other domains (such as automobile design). Chairs may also contain analogies to objects (e.g. the resemblance of the **Chair_One** shell to a soccer ball), animals (e.g. **Ant** chair), or plants (e.g. **Tulip** chair). The chair may convey messages, such as criticisms and satires (e.g. **Louis 20** chair).

Chairs may also perform social functions. When arranged together, they create patterns of behaviour and communication between their users. For instance, chairs arranged in a circle (e.g., in a round dining table) promote more interaction than chairs arranged in a line (e.g., in an airport waiting room). It is recommended for the layout of a sitting space to be displayed as follows (**Fig. 4.12**, right):

> *"Place each sitting space in a position which is protected, not cut by paths or movement, roughly circular - not too strongly - with paths and activities around it, so that people naturally gravitate toward the chairs and cushions loosely in the circle, and have a few too many." (Alexander et al. 1977, p.859)*

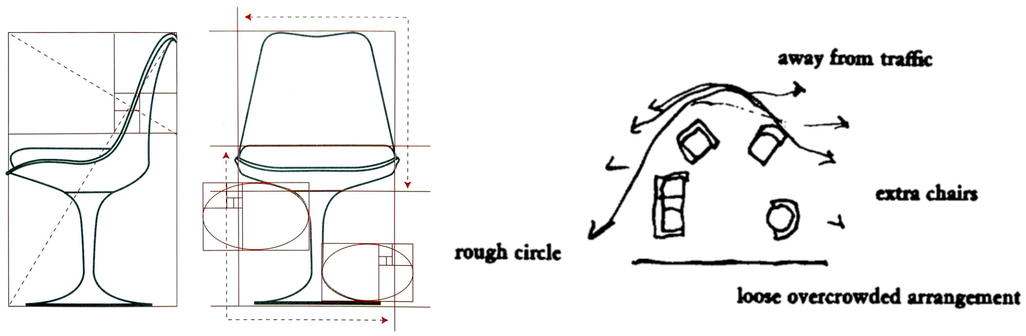


Fig. 4.12 Aesthetic analysis – on the left (Elam 2001); and symbolic analysis – on the right (Alexander et al. 1977, p.859)

Symbolic and aesthetic motivations are sometimes more significant than logical and rational reasons for consumers purchasing a chair. For example, the *Hardoy* chair, designed by Ferrari-Hardoy, Kurchan and Bonet in 1938 (Fiell & Fiell [1997] 2012, p.187), is ergonomically problematic but it is a sales success, perhaps due to the analogy of a protective womb given by the concave seat bag (Rykwert 1975).

> *"If the shape of a chair communicates the right message, we don't care how it feels physically. How it feels emotionally is what counts". (Cranz [1998] 2000, p.67)*

4.4.2 Materials

The material constrains the form (Ashby & Johnson 2002), and is commonly used as a design driver to explore new geometrical and structural possibilities. Until the 19th century, the chair was mainly used as a symbol of power; therefore changes mostly addressed decoration and craftwork. The form and structure of the chair only comprised significant modifications in the 20th century, resulting from the invention of new materials and new manufacturing techniques.

Materials can be divided into two major categories: rigid (applied in frame and/or panels) and flexible (typically applied in panels). Materials can then be subdivided into four main categories: wood, metal, plastic, and textile (Thompson 2007). Ceramics and glass materials were disregarded in this ontology, since chairs mostly use resistant and lightweight materials (to address the movable function)[9]. More specific types of materials (e.g. types of wood) were also not addressed, but can be consulted in the database of the **Multipurpose Chair Sample**.

The configuration of the raw material comprises the following types: solid (e.g. wood), sheet (e.g. plywood), profile (e.g. rod or tubular steel), and liquid (e.g. die-cast aluminium). The manufacturing technologies can be divided into forming (e.g. bending, moulding, and milling), cutting, joining and finishing (Thompson 2007). The latter two technologies were not considered in this ontology (but may be consulted in the sample database), as well as the production type (mass, batch, and one-off production), and the techniques (craft and industrial). The materials, technologies and their applications are schematized in **Fig. 4.13** and summarized below:

1) *Wood*: is a natural and fibrous material. Until the mid-19th century, the chair frame was mostly made of solid wood; afterwards a series of new techniques was introduced in chair design, such as bended wood and moulded plywood. The wood class can be characterized by the configuration (solid wood and plywood), and by the manufacturing technology (e.g., bending, milling and moulding). Other related materials which could be included in this class are cork and paper.

2) *Metal*: is a hard, flexible and ductile material. The cast iron was typically applied in chairs in 18th and 19th centuries. In the 1920s, the application of tubular steel in chairs allowed them to become lighter and mass-produced and triggered the introduction of the groundbreaking cantilever chair. Metal can assume different configurations (tubular, rod/wire, sheet or liquid) and be shaped by several manufacturing techniques (such as bending and moulding).

3) *Plastic*: is a flexible, lightweight and versatile material. Plastic mass-produced furniture only started to be developed after World War II, being the **DAX** chair one of the earliest successful examples. The research on chair design at the time addressed an ob-

[9] There are some sparse examples of glass chairs, such as the *Ghost* chair designed by Cini Boeri and Tomu Katayanagi in 1987 (Fiell & Fiell [1997] 2012, p.526).

session in achieving a one-piece plastic chair, which was finally accomplished with the **Bofinger** chair (1965) and the **Panton** chair (1967). The plastic is typically shaped by moulding techniques, including several methods (e.g. injection moulding).

4) *Textile*: is a flexible material, which can be natural (e.g. leather) or synthetic (e.g. nylon). Textiles (or fibers) have been applied to chairs for decades, for decoration or for adding comfort. These materials are commonly applied in Seat and Back supports, and can be sewed, woven or upholstered (using different materials in covering and filling).

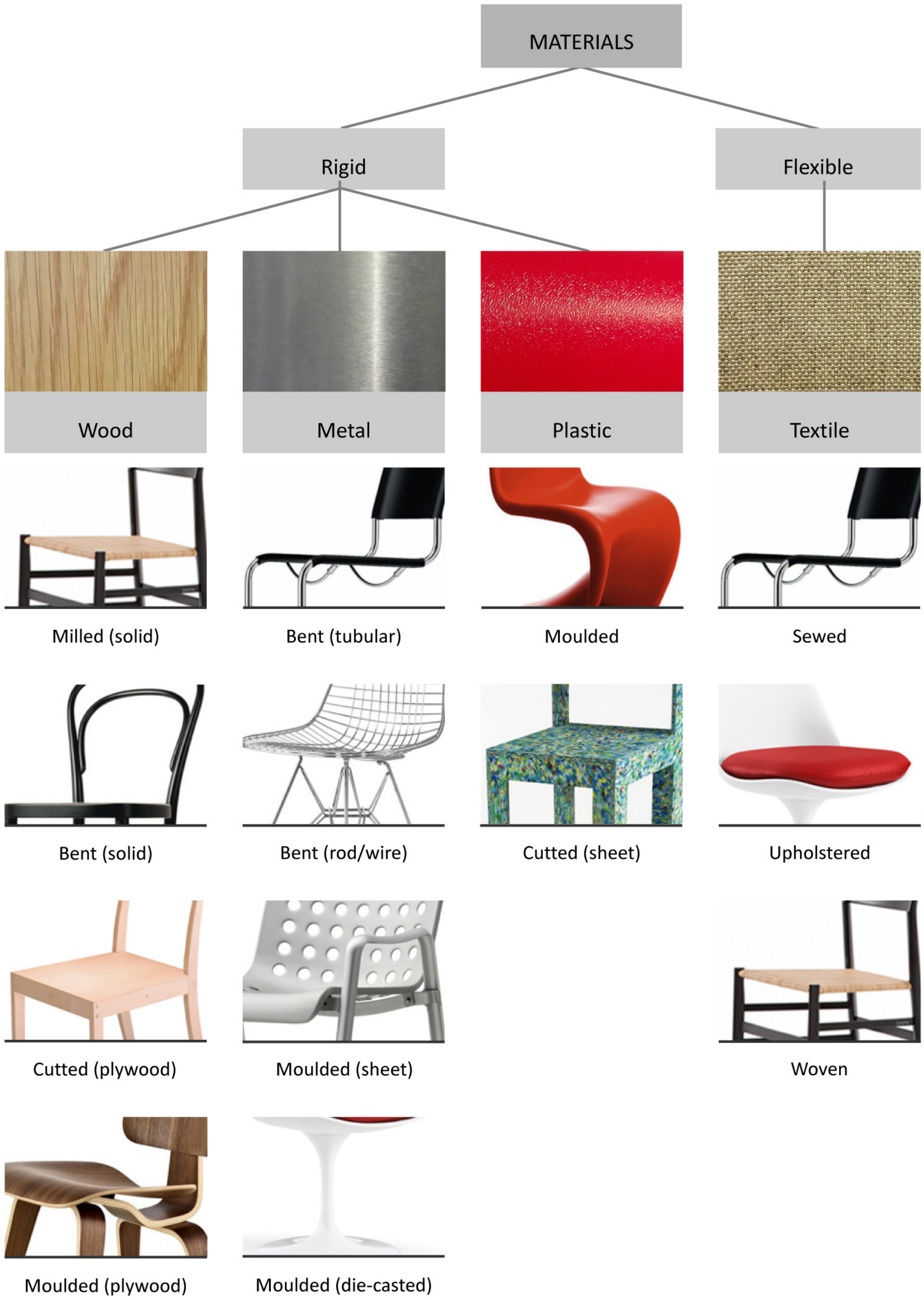


Fig. 4.13 Diagram of materials

Physical Properties

The physical properties of a product are related to the materials and to the technical performance. These include mechanical (e.g. weight, strength, durability), optical (e.g. colour, luminosity, reflectivity), environmental, chemical, thermal and acoustical properties. The properties of the chair must follow specific requirements, given by standards and recommendations, in order to guarantee the quality of the product. Some guidelines are listed below:

1) *Weight*: in order to be moveable, the chair should have a maximum weight of 23.18 kg (51 pounds), according to the Recommended Weight Limit, which is the maximum load recommended for lifting objects with both hands for a large period of time, without an increased risk of developing back pain (NIOSH 2007). The lightest chair, according to the Guinness World Records (2008), is *Estrema*, designed by Massimiliano Della Monaca in 2008. The chair weights 0.617 kg.

2) *Strength and durability*: the chair needs to ensure enough structural rigidity in order to accomplish the premise of accommodating a person for a certain period of time. The international standard ISO 7173 (ISO 1989) provides guidelines to measure the strength and durability of a chair, through tests where loads simulate short and long periods of usage. The minimum values of static loads in Seat and Back are, respectively, 1100 N and 410 N.

3) *Stability*: the stability of the chair can be determined according to the guidelines of the standard ISO 7174-1 (ISO 1988).

4) *Safety*: safety and health requirements include features such as stability, strength, durability and shape. For instance, sharp edges and corners should be avoided; according to the standard EN 1335-2 (CEN 2009), the corners should have a minimum radius of 2 mm. The resistance to environmental conditions, such as sun, wind, and precipitation, is particularly relevant in outdoor chairs.

5) *Environment*: sustainability includes three main concerns: reduce, reuse and recycle. Those principles are applicable not only to design (e.g. use recycled and recyclable materials) but to the entire life-cycle of to the product, including production (e.g. reduce water, energy, and chemical emissions), distribution (e.g. reduce emissions and optimize packaging – in order to increment the number of products transported at one time), usage (e.g. increment the product lifetime) and disposal (e.g. design easily disassembled products).

4.5 Conclusion

This chapter presented an ontological classification of multipurpose chairs. The ontology included different features, divided into two sections. The first section addressed the following features: parts (given by a functional decomposition of the chair), geometry (comprising dimensions and shape), types and styles (considering different classifications of chairs), and generation (focused on the composition sequence of the parts). The second section comprised the following features: functions (primary, practical, formal/aesthetic and symbolic), and materials (including construction techniques and physical properties).

The ontology of section one is formally represented by schemas, descriptions and diagrams. The formalism includes three abstraction levels: a generic ontology (applicable to furniture), a specific ontology (applicable to multipurpose chairs), and an application ontology (applicable to particular chairs). Concepts in the ontology are applicable in the three levels, for example: front rail, seat front rail, and the chair **214** seat front rail (from general to particular). Section two was not so exhaustively defined and thus was not used in the subsequent stage of the computational model (**Multipurpose Chair Grammar**).

The main contribution of this chapter is an ontology which encodes the chair design knowledge by a classification of entities, their properties and relations. The ontology defines what a chair is and what a chair is not, in terms of similar and distinctive characteristics. It encompasses a clear definition of the terms, an overall coherence (as it is based on a high-level ontology), supports different abstraction levels and is extendible to further conceptualizations. Moreover, the ontology can be used to generate new solutions.

On the negative side, the ontology comprises a deterministic categorization, not allowing intermediate ambiguous classifications (for e.g., chairs with one leg at the seat level and four legs in the base level), or more flexible classifications (for e.g., the support parts can be composed by linear elements beyond the planar elements described, as in the case of a slat seat chair).

Future work comprises two distinct directions. The first one addresses the implementation of the ontology in a digital system. This would allow linking the three different representations (schemas, tables and diagrams), sharing the ontology, connecting the ontology with the grammar, and the possibility of including automatic learning capabilities. The second direction includes the extension of the ontology to incorporate other features, such as optional shape parameters (e.g. leg width – distance between legs), and further variables to address a higher level of shape detail (e.g. section angle, other section shapes, legs taper in one direction, legs height, and curves). The ontology could also feature the connections between parts, and other methods to generate the form (beyond the addition of parts). Finally, features included in the **Multipurpose Chair Sample** should be addressed by the ontology, such as: specific types of materials, physical properties (e.g. colour and recyclability), joining and finishing manufacturing techniques, price, packaging (weight and dimensions), and identification details (designer, producer, manufacturer, seller, and client).

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4.7 Appendixes

Appendix 4.A Meta-Ontology

- **Appendix 4.A.1** Parts (table)
- **Appendix 4.A.2** Geometry (table)
- **Appendix 4.A.3** Types (table)
- **Appendix 4.A.4** Geometry (schema)
- **Appendix 4.A.5** Types (schema)

Appendix 4.B Multipurpose Chair Ontology

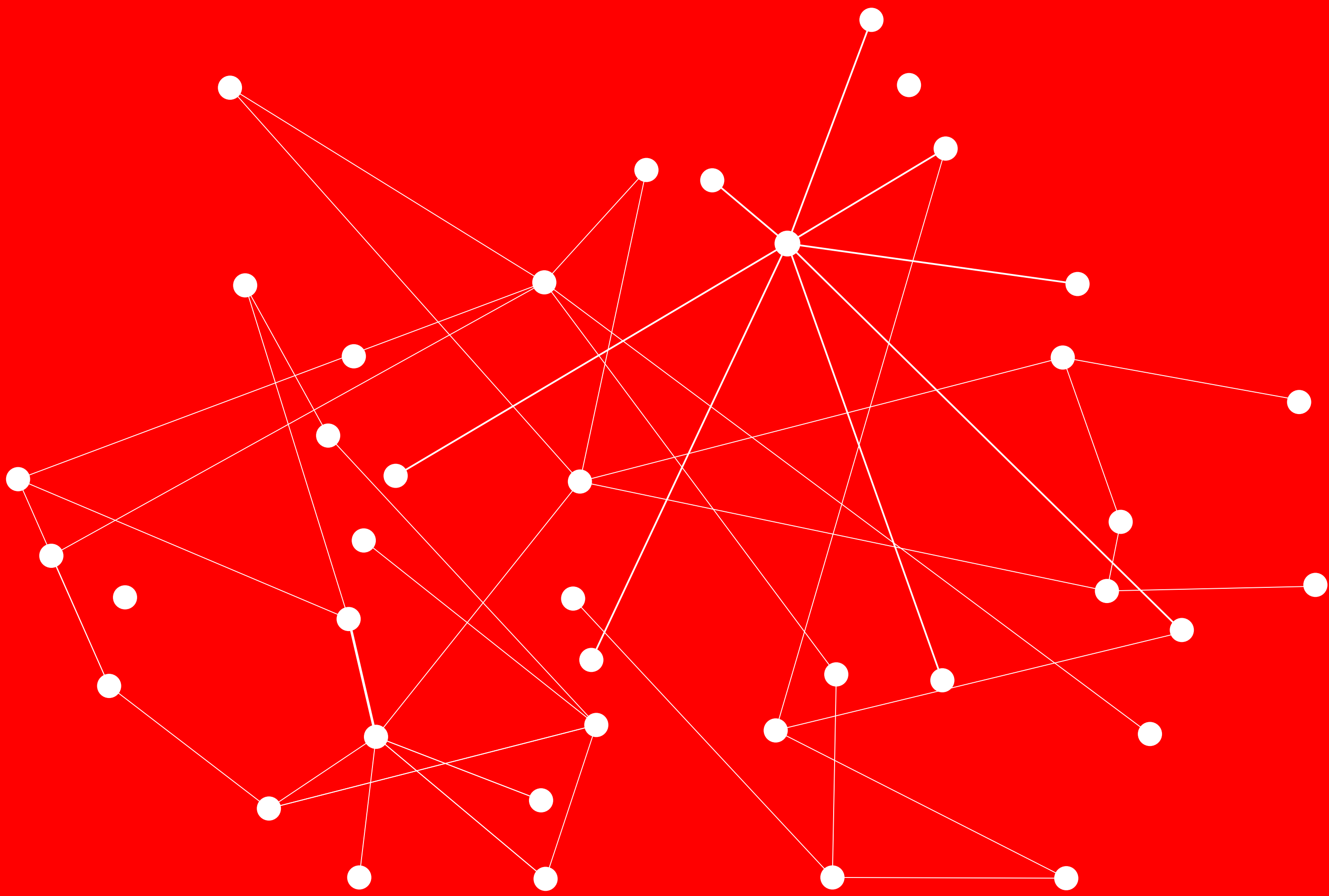
- **Appendix 4.B.1** Parts/Geometry/Generation (table)
- **Appendix 4.B.2** Types (table)
- **Appendix 4.B.3** Parts (schema)
- **Appendix 4.B.4** Types (schema)
- **Appendix 4.B.5** Parts (diagram)
- **Appendix 4.B.6** Types (diagram)
- **Appendix 4.B.7** Generation (diagram)

Appendix 4.C Design 214 Ontology

- **Appendix 4.C.1** Parts (diagram)
- **Appendix 4.C.2** Types (diagram)

Appendix 4.D Others

- **Appendix 4.D.1** Anthropometric Dimensions (comparison table)



Multipurpose Chair Grammar

5

5 MULTIPURPOSE CHAIR GRAMMAR

Shape grammars are rule-based formalisms that allow the description and generation of a large variety of designs. This chapter presents a parametric set grammar (a particular type of shape grammars) for the analysis and generation of multipurpose chairs. This generic grammar was customized into three specific grammars, which describe and generate designs within three styles (of two designers and one manufacturing company), one hybrid and one common grammar. The grammar was designed according to an analytic and ontology-based method. Moreover, as the grammar was being incrementally developed along four versions, the transformation method was also employed. The grammar was tested in terms of its descriptive, analytic and generative capabilities.

5.1 Introduction

A Shape Grammar (SG) is a formalism to describe and generate designs, through if-then shape rules (Stiny 1980a). Because the formalism is based on visual reasoning, it has been claimed to be suitable to support the creative design process (Flemming 1989). An SG can define a language of designs, comprising for e.g. a style (Knight 1980), a brand (Pugliese & Cagan 2002), a product class (Agarwal & Cagan 1998), or a design collection (Castro e Costa & Duarte 2014).

There are three main methods for developing an SG (Knight 1999a): (1) analytic grammars (Stiny & Mitchell 1978) are developed upon the analysis of a corpus of designs of an existing language, and generate existing and new designs within the language; (2) synthetic grammars (Stiny 1980b) are developed from the synthesis of a given vocabulary, and generate a new language of designs; and (3) transformation grammars are developed from the transformation of a given grammar (Knight 1989), and can lead to other existing or original languages.

There are several types of SGs. An SG can contemplate one language of designs (specific SGs) or multiple sub-languages of designs (generic SGs). Generic SGs (Li 2001) can be restricted to specific SGs, and specific SGs can be extended to generic SGs. Furthermore, the overlapping of specific SGs lead to new grammars. Six types of grammars (Garcia & Romão 2016) are illustrated in the Venn diagram of **Fig. 5.1** (sets labelled inside shaded areas do not contain subsets, and sets labelling lines contain all the subsets inside it): (1) *specific grammars*: the overlapping sets A and B; (2) c*ommon grammar*: the intersection $A \cap B$ (comprising the grammar features – rules, parameters, labels, etc. – that are common to A and B); (3) *hybrid grammar*: the union $A \cup B$ (comprising all the grammar features of A and B); (4) d*istinctive grammars*: the subtraction A-B and B-A (comprising the grammar features of one grammar but not of the other); (5) g*eneric grammar*: the universal set U (comprising more than the grammar features of A and B); (6) c*omplement grammar:* the complement $U-(A \cup B)$, comprising the grammar features that are neither from A nor from B.

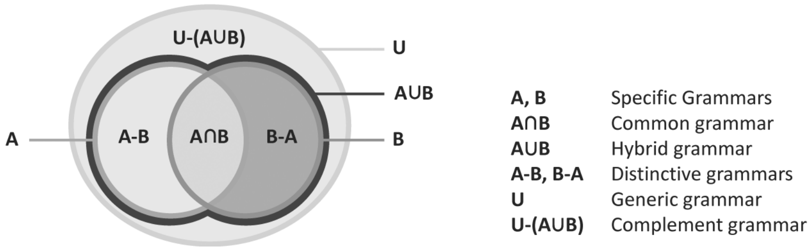


Fig. 5.1 Six types of grammars

The paradigm of generic/specific SGs has been applied to product design, to address design classes which can be restricted to more specific subclasses. For instance, the motorcycle grammar is customizable to a particular brand (Pugliese & Cagan 2002), and the cross-over vehicle grammar (Orsborn et al. 2006) can be restricted to three vehicles subclasses and hybrid classes. In chair design, there are two specific SGs addressing the backrest inner frame design of two styles, Hepplewhite (Knight 1980) and Thonet (Barros, Duarte & Chaparro 2011), and a more generic SG which addresses the product class of office chairs (Hsiao & Chen 1997).

This chapter describes the Multipurpose Chair Grammar (MCG), a generic ontology-based SG which addresses design types, and is customizable to specific SGs, which address specific design styles. The MCG is intended to be applied as a tool for designers in the concept phase of chair design. The grammar comprises the fourth stage of the computational model (mentioned in the **Introduction** chapter), and its development went through four main versions. The grammar versions are summarized in **Table 5.1** and are described below.

1) **Version 0.1**: *Daciano Chair Grammar* (DCG), a specific SG which characterizes the individual style of the designer Daciano da Costa. It was developed from the analysis of a corpus of 5 multipurpose wooden frame chairs of the designer.

2) **Version 0.2**: *Daciano-Jasper Hybrid Grammar* (DJHG), a hybrid SG which characterizes two individual styles. It was developed by extending the DCG to incorporate 5 multipurpose wooden frame chairs of the designer Jasper Morrison. The DJHG contains two specific SGs: the DCG and the *Jasper Chair Grammar* (JCG);

3) **Version 1.1**: *Iconic Chair Grammar* (ICG), a specific SG developed from the analysis of a corpus of 26 iconic chairs, representing different types. The corpus has a design common to the corpus of the JCG. This version included the version 1.1.1, characterized by the incorporation of an existing specific SG – the *Thonet Chair Grammar* (TCG), developed by Barros, Duarte & Chaparro (2011). This incorporation required a slight extension of the ICG;

4) **Version 1.2**: *Multipurpose Chair Grammar* (MCG), a generic SG which contains seven other grammars. Four are analytic specific SGs (DCG, JCG, TCG, and ICG); two result from the overlapping DCG and JCG – a common SG (DJCG) and a hybrid SG (DJHG); and one is a complement SG – *Synthetic Chair Grammar* (SCG), containing rules and parametric ranges that none of the other analytic grammars use.

Table 5.1 Details of the MCG versions

Version	Grammar	ID	Method	Type	Corpus	Rules	Parameters
0.1	**Daciano Chair Grammar**	**DCG**	**Analytic**	**Specific**	**5**	**24**	**11**
0.2	**Daciano-Jasper Hybrid Grammar**	**DJHG**	**Transformation**	**Hybrid**	**10**	**41**	**26**
	Daciano Chair Grammar	DCG	Transformation	Specific	5	33	16
	Jasper Chair Grammar	JCG	Analytic	Specific	5	35	21
1.1	**Iconic Chair Grammar**	**ICG**	**Analytic**	**Specific**	**26**	**51**	**56**
1.1.1	**Iconic Chair Grammar**	**ICG**	**Transformation**	**Generic**	**28**	**52**	**57**
	Thonet Chair Grammar	TCG	Transformation	Specific	3	11	15
1.2	**Multipurpose Chair Grammar**	**MCG**	**Transformation**	**Generic**	**37**	**108**	**61**
	Daciano Chair Grammar	DCG	Transformation	Specific	5	26	23
	Jasper Chair Grammar	JCG	Transformation	Specific	5	29	38
	Thonet Chair Grammar	TCG	Transformation	Specific	3	23	26
	Iconic Chair Grammar	ICG	Transformation	Specific	26	62	55
	Daciano-Jasper Hybrid Grammar	DJHG	Hybrid	Hybrid	10	38	39
	Daciano-Jasper Common Grammar	DJCG	Common	Common	**N/A**	17	39
	Synthetic Chair Grammar	SCG	Synthetic	Complement	**N/A**	41	50

The eight grammars of **Version 1.2** are represented in a Venn diagram illustrated in **Fig. 5.2**. The sizes of the five major sets are proportional to the rule number of the grammars, and the intersections size is proportional to the common rules between the grammars. Whereby, sets: (i) labelled inside shaded areas do not contain subsets (i.e., SCG, DJCG, and DJHG); and, (ii) labelling lines contain all the subsets inside it (i.e., ICG, JCG, DCG, TCG, and MCG). The figure indicates that only the JCG is fully contained in the ICG.

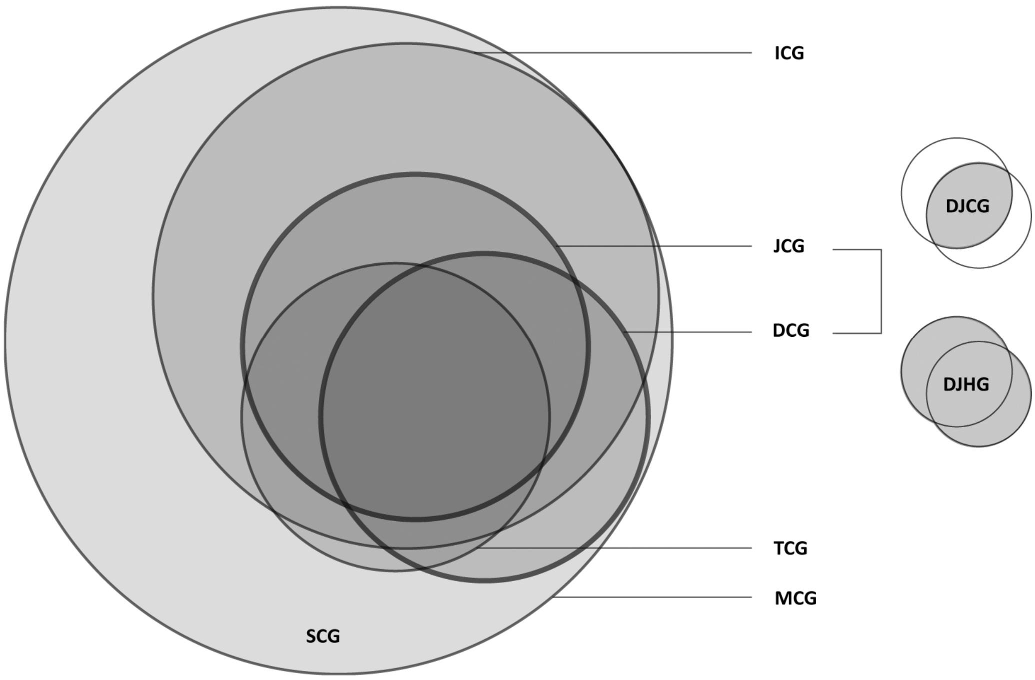


Fig. 5.2 Venn diagram representing the MCG and other seven sub-grammars

The chapter describes the last version of the grammars, structured as follows: firstly, the MCG is described; secondly a meta-grammar is addressed; thirdly the sub-grammars are characterized; and fourthly some designs generated by the grammars are presented.

5.2 Multipurpose Chair Grammar

5.2.1 Grammar Characterization

SGs can be classified according to several different categories. The Multipurpose Chair Grammar (MCG) was characterized according to an SG classification framework (Garcia 2016), summarized below.

1) *Application Domain*: the MCG is a design grammar (Pauwels et al. 2015), as it describes and generates designs within a product language. The purpose of the grammar is to be used as a tool for design students and practitioners.

2) *Grammar Method*: the MCG is a generic SG, whose language characterizes the product class of symmetric multipurpose chairs. The MCG is customizable to specific SGs which characterize individual designer's styles and group styles. The MCG is based on the ontology detailed in the chapter **Multipurpose Chair Ontology**. The development of the MCG followed three methods: (i) analysis method, since rules were mainly based on the analysis of a corpus of designs (described in the chapter **Multipurpose Chair Sample**), (ii) synthesis method, since some rules are based on new combinations of the elements of the vocabulary, and some parameters are based on design patterns (namely anthropometric standards), and (iii) transformation method, since rules and parameters were redefined from previous versions.

3) *Shape Properties*: the MCG is a parametric set grammar. (i) Parametric SGs (Stiny 1980a) are an extension of SGs, since they work with shape schemas instead of shapes. Shape schemas describe families of shapes with similar topologies. A shape schema is defined by variables; when values are assigned to those variables, a shape is obtained. (ii) Set grammars (Stiny 1982) are a restriction of SGs, since they only work with indecomposable shapes. Unlike SGs, set grammars do not allow emergence. Emergence is the ability to recognize and use shapes that are not predefined in the vocabulary but arise during the computation, from the combination of subshapes. Since set grammar rules can be represented as symbolic objects, they are more suitable for implementation (Stiny 1982), reducing performance, usability and utility problems. However, set grammars reduce reinterpretation, ambiguity, and unpredictability (Knight 2003).

4) *Shape Elements*: the grammar represents designs by points, lines, planes and solids. There are two visualization modes: the wireframe mode describes the inner skeleton of the designs, using lines (rectilinear and curvilinear) and planes (rectilinear); the solid mode describes the designs by solids, obtained by thickening the skeleton. The designs comprise a low level of shape detail; the abstraction level was defined in the previous chapter (**Multipurpose Chair Ontology**).

5) *Dimensional Space*: the shape elements are edited in a three-dimensional space. The shapes and designs are represented in an axonometric (trimetric) projection.

6) *Shape Qualities*: the MCG is a labelled weighted grammar. Labels add a symbolic representation to the graphic depiction of the chair parts, and are used to control rule application. Weights (thickness and colour) are used to distinguish the three different configurations of the parts, described in the **Multipurpose Chair Ontology**: (i) *guides* are represented by labelled weighted (grey) lines, (ii) the *frame* is represented by labelled weighted (double-thick) black lines, and (iii) *panels* are represented by labelled weighted (grey) planes. Therefore, the algebras (Stiny 1992) used by MCG are: $U_{13}V_{13}W_{13}$ (guides), $U_{13}V_{13}W_{13}$ (frame), $U_{23}V_{23}$,W_{23} (panels), and U_{33} (solids). Moreover, lines are defined by labelled points $U_{03}V_{03}$ (guides and frame).

7) *Design Strategy*: the MCG employs a grid strategy (Knight 1999a). The initial shape determines an underlying grid, which controls the placement of shapes (the parts of the chair) that will be subsequently added by the grammar's rules. Within this strategy, the boundary is defined from the beginning, unlike the additive strategy, where the boundary is not fixed and is constantly being redefined by the addition of shapes. The guides are used to restrain the placement of the chair parts to correct anthropometric standards.

8) *Rule Format*: the majority of the rules used in MCG are from the additive type. Each additive rule adds a part of the chair, as specified in the chapter **Multipurpose Chair Ontology**, and allows the user to manipulate its parameters (when applicable). The initial shape does not contain any parts; the parts are successively added, step-by-step, until the final design is reached. Other types of rules used by the MCG will be later detailed.

9) *Rule Ordering*: the MCG is a nondeterministic grammar (Knight 1999b), since there is not a mandatory sequence for rule application. At each derivation step, several designs can be generated, depending on which rule to apply and on which values are assigned to the parameters. This freedom of choice was intended to contemplate different design strategies, suitable to a particular designer or a particular design problem. Meanwhile, there are some mandatory sequences; for instance, the inner frame can only be added after the outer frame is placed.

10) *Compound Representation*: the MCG is a description grammar (Stiny 1981). Each part of the chair has a corresponding description (assigned by labels), adding meaning to the shape. The description of a design evolves from the initial shape to the final solution. The final design is described by a list of parts and parameters.

11) *Implementation*: the MCG is implemented in a digital environment. The implementation allowed the grammar to be tested. Moreover, the digital system comprises an increased flexibility, speed and efficiency in the generation of the designs. The implementation will be detailed in the next chapter (**The ChairDNA Design Tool**).

5.2.2 Initial Shape

The initial shape of the MCG (**Fig. 5.3**) contains the guides of the Seat, Back, Legs and Base. The guides correspond to an underlying grid which defines the Seat and Back bounding perimeters and the bounding box underneath the seat where the Legs are placed. These guides can be parametrically transformed in four MCG rules, as it will be later described. The symmetry plane θ and the axis icon are not part of the initial shape; they are merely indicative. Because the language only addresses bilaterally symmetric designs, the geometry of the parts will be defined in the left side of the plane θ (where x coordinates are negative); the elements on the right side are automatically mirrored. The axis icon indicates the absolute origin (located in the horizontal projection of the midpoint of the seat front edge) and the orientation of the coordinate system.

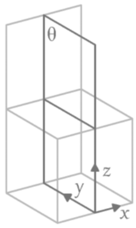


Fig. 5.3 Initial shape

5.2.3 Rules

Rules are from the type LHS (left-hand side) → RHS (right-hand side), where LHS and RHS are both shape schemas, with the characteristics defined by Stiny (1980a). The MCG has 108 rules, divided by four types: 100 additive rules, 1 subtractive rule, 3 condensed rules and 4 transformative rules. The additive rules comprise the addition of 39 chair parts and 6 guides; the same part can be added by different rules (that is, from different LHSs). The subtraction rule is the termination rule, which erases the guides. The condensed rules, which subtract and add a shape, are the solid mode rules. The transformation rules (the guides of the Legs, Seat, Back, and Base) contemplate parametric transformations. Moreover, considering the grammar method, there are rules which describe at least one part of a design of the corpus (analytic rules), and rules which do not describe any part of any design of the corpus (synthetic rules).

Grammars can have, beyond shape, additional conditions for rule application (Orsborn et al. 2006). In the MCG, the conditions are displayed in the LHS of the rule, to distinguish two rules that add the same part (in the RHS). The conditions used in the MCG, and the respective logic symbols, are the following:

1) *Negative condition:* the rule is applicable if a given shape does not exist (¬);

2) *Geometric condition I*: the rule is applicable if a point is embedded in (or is an element of) a line (∈) or if a point does not lie on a line (∉);

3) *Geometric condition II*: the rule is applicable if a point is coincident (or identical) to another (≡) or if a point is not coincident to another (≢);

4) *Parametric condition*: the rule is applicable if a parameter is equal (=) to a value, or if a parameter is not equal (≠) to a value;

5) *Compound condition*: combines two or more of the aforementioned conditions; the rule is applicable if all the conditions are true (∧); or if at least one of the conditions is true (∨).

The rules of the MCG are grouped in eight sets: Legs, Seat, Back, Leg-Stretchers, Leg-Base, Arms, Solid Mode, and Termination. The rule sets (excluding the last two) correspond to the groups of parts mentioned in the **Multipurpose Chair Ontology**. The rule schemas and the respective parameters are described and illustrated in the next sections, for each set. The schemas are displayed according to the default parameters, except in cases where a specific feature needs to be exemplified. The rules are labelled with a long name and an ID (acronym). The labels of the guides and points are omitted, for clarity. The rule parameter IDs are indicated in the rule schema and are subsequently specified in a table detailing their units, ranges (composed by integer numbers ℤ) and default (def.) values. The rule parameters control the geometry of parts, addressing sizes, positions, shapes, and numbers of parts. Parameters include linear, angular and radial dimensions, expressed in three units (millimetres, degrees, and percentages). Some parameters are common to more than one rule, for rules that add the same part of the chair.

Legs

The Legs rule set contains 9 rules, which are illustrated in **Fig. 5.4**, and 8 parameters, illustrated in **Table 5.2**. The Legs rules can be divided into three groups: (1) guides (Legs Guides); (2) frame (Front and Back Leg), and (3) panels (Front, Back, Side and Radial Leg Panels).

(1) The Legs Guides parameters are the same used in Legs Front and Back, described below.

(2) The parameters of the Leg Front (**LF**) and Leg Back (**LB**) rules dictate the positioning of the endpoints of the legs. In the Leg Front, the Width and Depth Spacing indicate the position of the top endpoint (SPF) in the seat plane, in relation to the seat corner (0%). The Width Spacing can range from the symmetry plane θ (-100%) to the same distance outwards (100%), and the Depth Spacing can range from the frontal (coronal) plane δ (-100%) to the same distance outwards (100%). The Splay and Rake angles indicate the position of the bottom endpoint (LBPF) in the base plane, in relation to the vertical (0%). The Splay Angle can range from the right edge of the Base (-100%) to the same distance outwards; the Rake Angle can range from the back edge of the Base (-100%) to the same distance outwards. In the Leg Back, the same logic is applicable for the positioning of the top endpoint (SPB) and the bottom endpoint (LBPB).

(3) The Leg Panels shape is controlled by the Legs Guides. The Leg Panel Front rule places a panel between the front legs (rule **LPF1**), except when the Rake Angle is -100 and the Base Rear Radius is not 0; in that case, the surface assumes a special configuration (rule **LPF2**). The same logic is applicable for the Leg Panel Back (rules **LPB1** and **LPB2**). The Leg Panels Side and Leg Panels Radial (rules **LPS** and **LPR**) place a panel connecting the front and back legs, from the same side or from opposite sides, respectively.

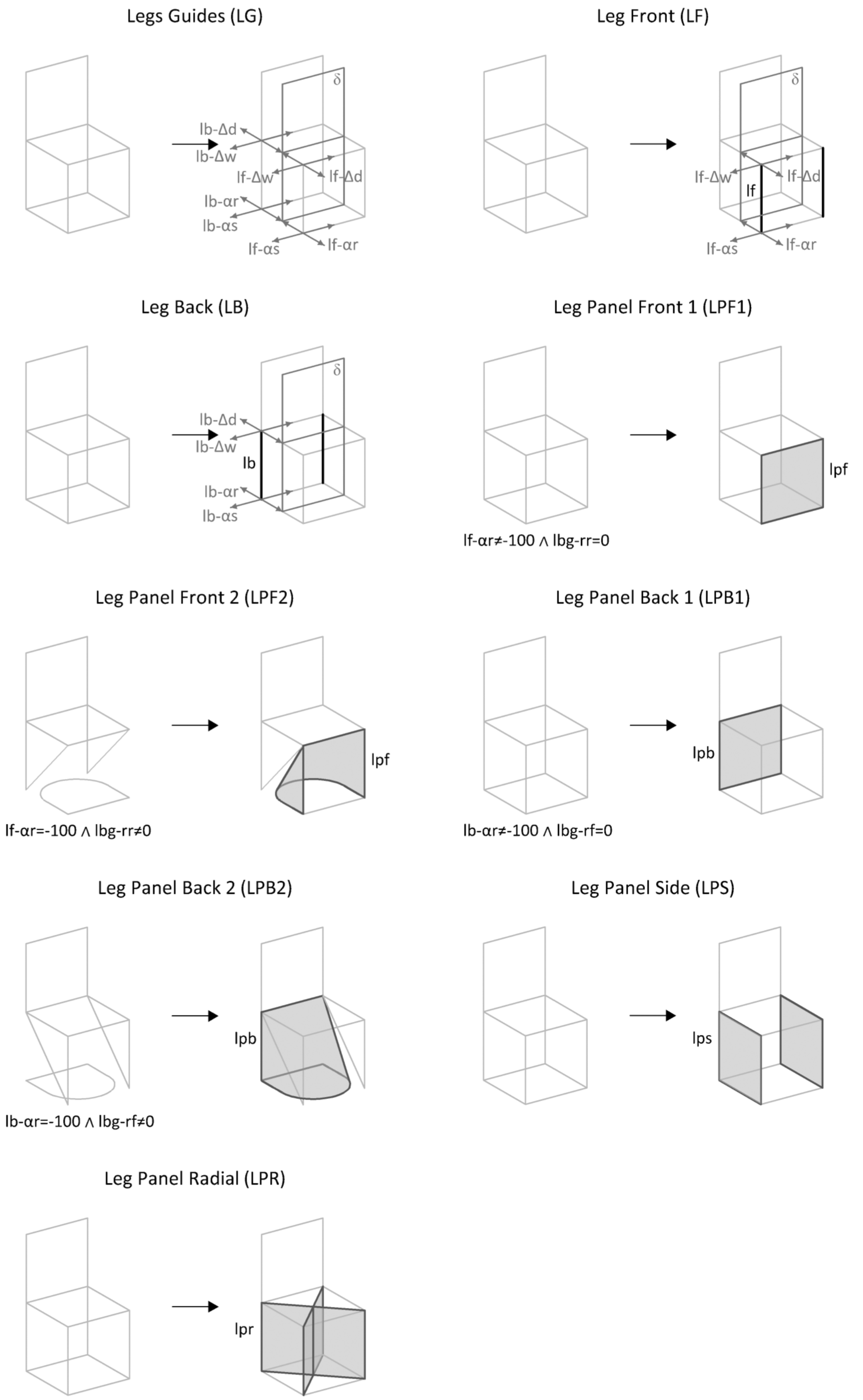


Fig. 5.4 Legs rules schemata

Table 5.2 Legs rule parameters

Legs Guides (LG), Front Leg (LF)

Parameter	ID	Unit	Range	Def.
Width Spacing	lf-Δw	%	[-100,100]	0
Depth Spacing	lf-Δd	%	[-100,100]	0
Splay Angle	lf-αs	%	[-100,100]	0
Rake Angle	lf-αr	%	[-100,100]	0

Legs Guides (LG), Back Leg (LB)

Parameter	ID	Unit	Range	Def.
Width Spacing	lb-Δw	%	[-100,100]	0
Depth Spacing	lb-Δd	%	[-100,100]	0
Splay Angle	lb-αs	%	[-100,100]	0
Rake Angle	lb-αr	%	[-100,100]	0

Seat

The Seat rule set contains 19 rules, which are illustrated in **Fig. 5.5** and **Fig. 5.6**, and 11 parameters, illustrated in **Table 5.3**. The Seat rules can be divided into four groups: (1) guides (Seat Guides); (2) outer frame (Seat Front, Back and Side); (3) inner frame (Seat Cross, Long and Radial); and (4) panels (Seat Panel).

(1) The Seat Guides rule (**SG**) parameters dictate its position (Height and Tilt Angle), size (Width and Depth), corners radii (Front and Rear) and Taper Width. The ranges of the Height, Width, Depth, and Tilt Angle parameters are related to anthropometric standards. The corner radius can range from zero (producing a straight corner) to half of the smallest edge of the guides (100%); this parameter is also applicable to the guides of Back, Leg-Stretchers, Leg-Base, and Arms. The Taper Width is the dimension of the rear edge in relation to the front edge; it can range from equal (0%) to zero (100%), i.e., from a rectangular to a triangular shape.

(2) The Seat Front, Back and Side are defined by the position of the top endpoints of the legs. If the top endpoint of the Leg Front (SPF) lies in the Seat Guides, the Seat Front assumes the guides shape (rule **SF1**); otherwise it linearly connects the top endpoints of the Leg Front (rule **SF2**). Analogously, if the top endpoint of the Leg Back (SPB) lies in the Seat Guides, the Seat Back assumes the guides shape (rule **SB1**); otherwise it linearly connects the top endpoints of the Leg Back (rule **SB2**). If both SPF and SPB lie in the Seat Guides, the Seat Side assumes the guides shape (rule **SS1**); otherwise it places a linear rail from the front or back legs (rules **SS2** and **SS3**).

(3) The Seat Cross can connect the Seat Side or Long rails (rules **SC1** and **SC2**). The parameter Depth Spacing dictates the position of the rail, from nearly the seat front edge (1%) to nearly the seat back edge (99%). The Seat Long can connect the Seat Front with the Back or the Cross rails (rules **SL1** and **SL2**), the Seat Back with the Cross rails (rule **SL3**), the Seat Front with the Leg Back (rule **SL4**), or the Seat Back with the Leg Front (rule **SL5**). The Width Front Spacing parameter dictates the position of the rail front endpoint in the front edge of seat, and the Width Rear Spacing of the rail back endpoint in the back edge of the seat; both from the symmetry plane θ (0%) to the seat side edge (100%). The Seat Radial can assume a diagonal, central or star configuration (rules **SR1**, **SR2** and **SR3**), depending on the position of the top endpoints of the legs (SPF and SPB). The parameter indicates the number of rails (between 3 and 5), for the star configuration.

(4) The Seat Panel outer shape is the same as the Seat Guides (rule **SP**).

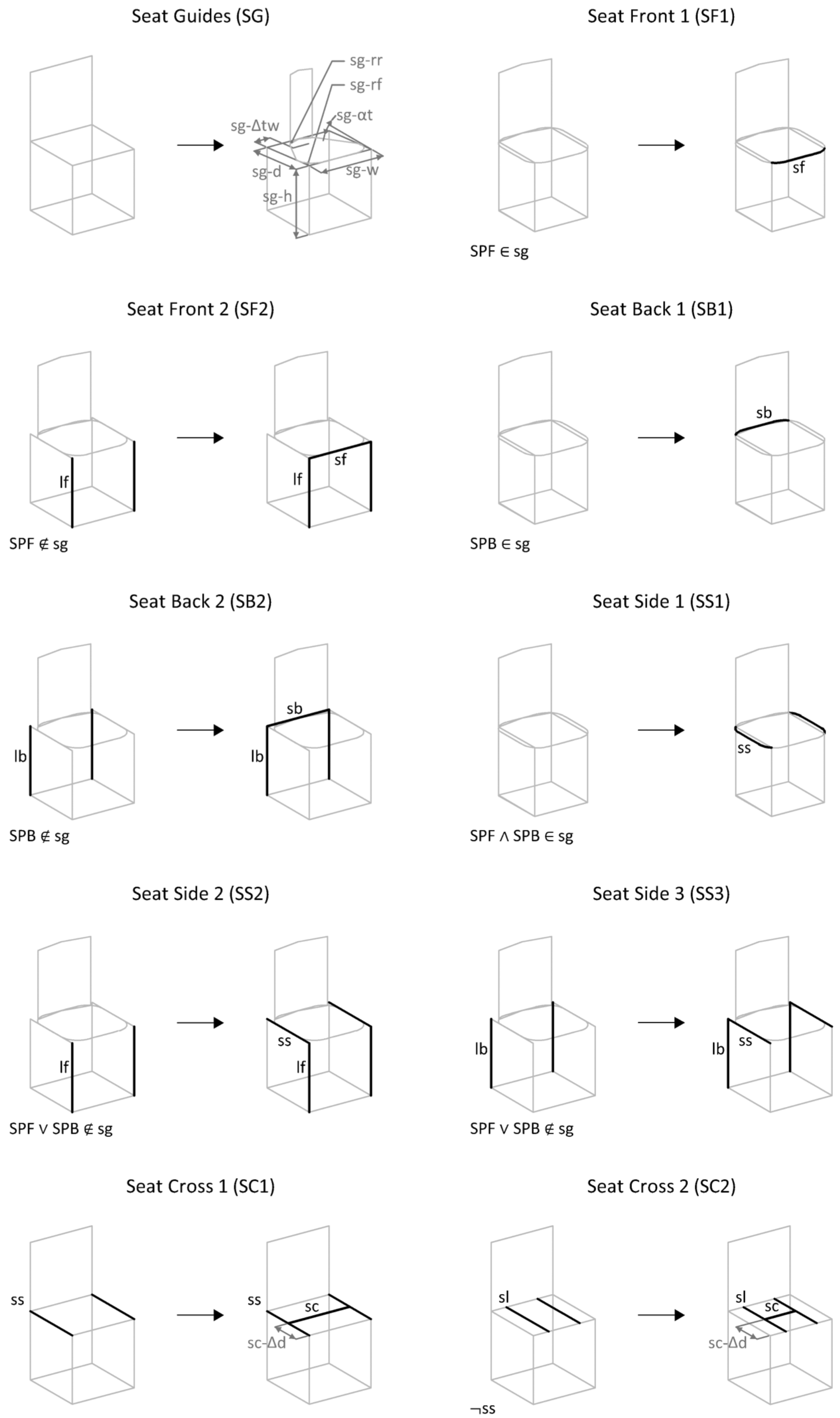


Fig. 5.5 Seat rules schemata (1/2)

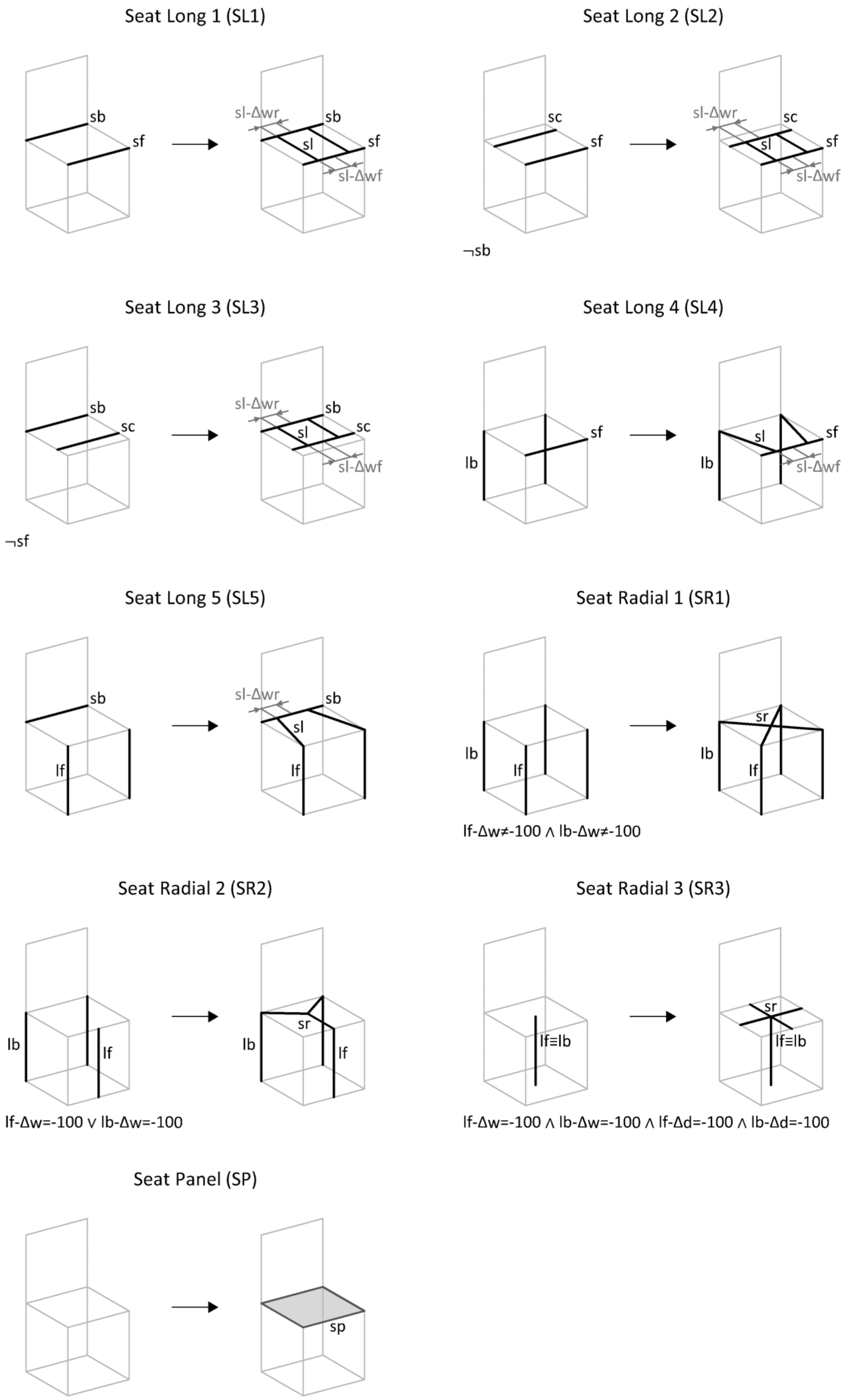


Fig. 5.6 Seat rules schemata (2/2)

Table 5.3 Seat rule parameters

Seat Guides (SG)

Parameter	ID	Unit	Range	Def.
Width	sg-w	mm	[406,560]	483
Depth	sg-d	mm	[406,508]	457
Height	sg-h	mm	[368,480]	424
Tilt Angle	sg-αt	°	[0,5]	0
Front Radius	sg-rf	%	[0,100]	0
Rear Radius	sg-rr	%	[0,100]	0
Taper Width	sg-Δtw	%	[0,100]	0

Seat Cross 1-2 (SC1-2)

Parameter	ID	Unit	Range	Def.
Depth Spacing	sc-Δd	%	[1,99]	50

Seat Long 1-5 (SL1-5)

Parameter	ID	Unit	Range	Def.
Width Front Spacing	sl-Δwf	%	[0,100]	50
Width Rear Spacing	sl-Δwr	%	[0,100]	50

Seat Radial 3 (SR3)

Parameter	ID	Unit	Range	Def.
Number	sr-n	N/A	[3,5]	4

Back

The Back rule set contains 18 rules, which are illustrated in **Fig. 5.7** and **Fig. 5.8**, and 11 parameters, illustrated in **Table 5.4**. The Back rules can be divided into four groups: (1) guides (Back Guides); (2) outer frame (Back Upright, Top and Bottom); (3) inner frame (Back Cross, Splat and Radial); and (4) panels (Back Panel).

(1) The Back Guides rule (**BG**) parameters dictate its position (Height Spacing and Back-Seat Angle), size (Width and Height), corners radii (Top and Bottom) and Taper Width. The ranges of the Height, Height Spacing, and Back-Seat Angle parameters are related to anthropometric standards. The Back Width (measured at the bottom) can range from 125mm (0%) to the Seat back corner (50%), and to the front endpoint of the Seat back arc (100%). The minimum value was adopted from the **S** chair and the maximum value from the **Basel** chair (both from the sample). The Taper Width is the dimension of the top edge in relation to the bottom edge; it can range from equal (0%) to zero (100%) to the double (-100%).

(2) The Back Upright can be an extension of the Leg Back, Seat Side or Armrest (rules **BU1**, **BU2** and **BU3**). The Height parameter dictates the position of the rail top endpoint (BPT), from nearly the back bottom edge (1%) to the back top edge (100%). The Back Top can connect the top endpoints of the Back Upright; if BPT is coincident to the top corner of the Back Guides (BBT) the rail follows the guides shape (rule **BT1**); otherwise assumes a linear shape (rule **BT2**). The Back Top can also connect the back endpoints of the Armrest with each other – producing a Back Cross Arm rail (rule **BT3**) or with the top endpoints of the Arm Support Back (rule **BT4**). The Back Bottom rule (**BB**) adds a rail with the shape of the bottom edge of the Back Guides.

(3) The Back Cross rule (**BC**) connects horizontally the Back Upright rails. The Height parameter dictates the position of the rail, from nearly the back bottom edge (1%) to nearly the back top edge (99%). The Back Splat can connect the Back Top with the Back Bottom, the Seat Back

or the Back Cross (rules **BS1**, **BS2** and **BS4**), can connect the Back Cross with the Back Bottom (rule **BS3**), or can be extended from the Seat Long, until the middle of the back (rule **BS5**). The Width Top Spacing parameter dictates the position of the rail top endpoint in the top edge of back, and the Width Bottom Spacing of the rail bottom endpoint in the bottom edge of back; both from the symmetry plane (0%) to the back side edge (100%). The Back Radial can assume a diagonal or central configuration, depending on the position of BPT (rules **BR1** and **BR2**).

(4) The Back Panel outer shape is the same as the Back Guides (rule **BP**).

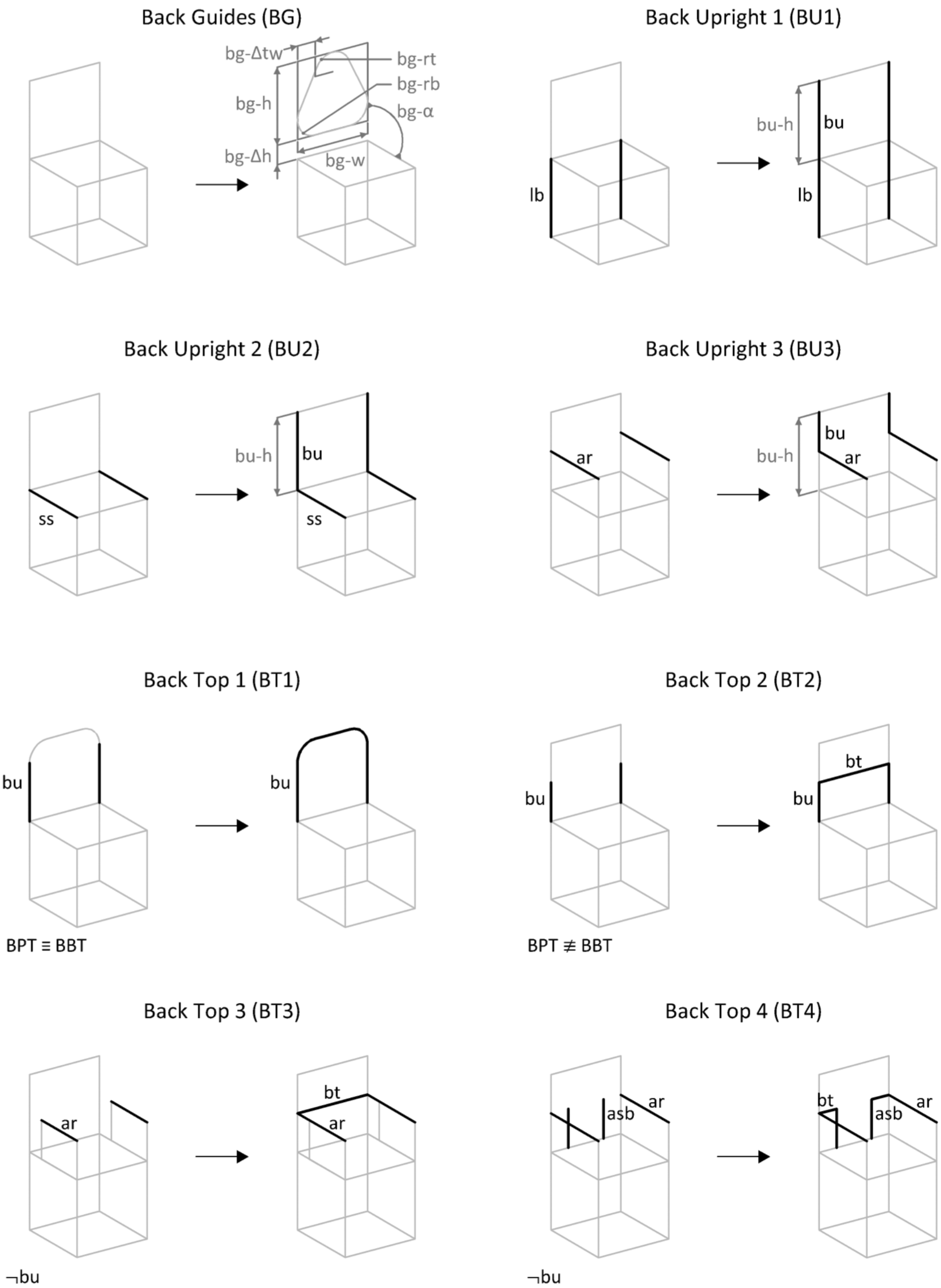


Fig. 5.7 Back rules schemata (1/2)

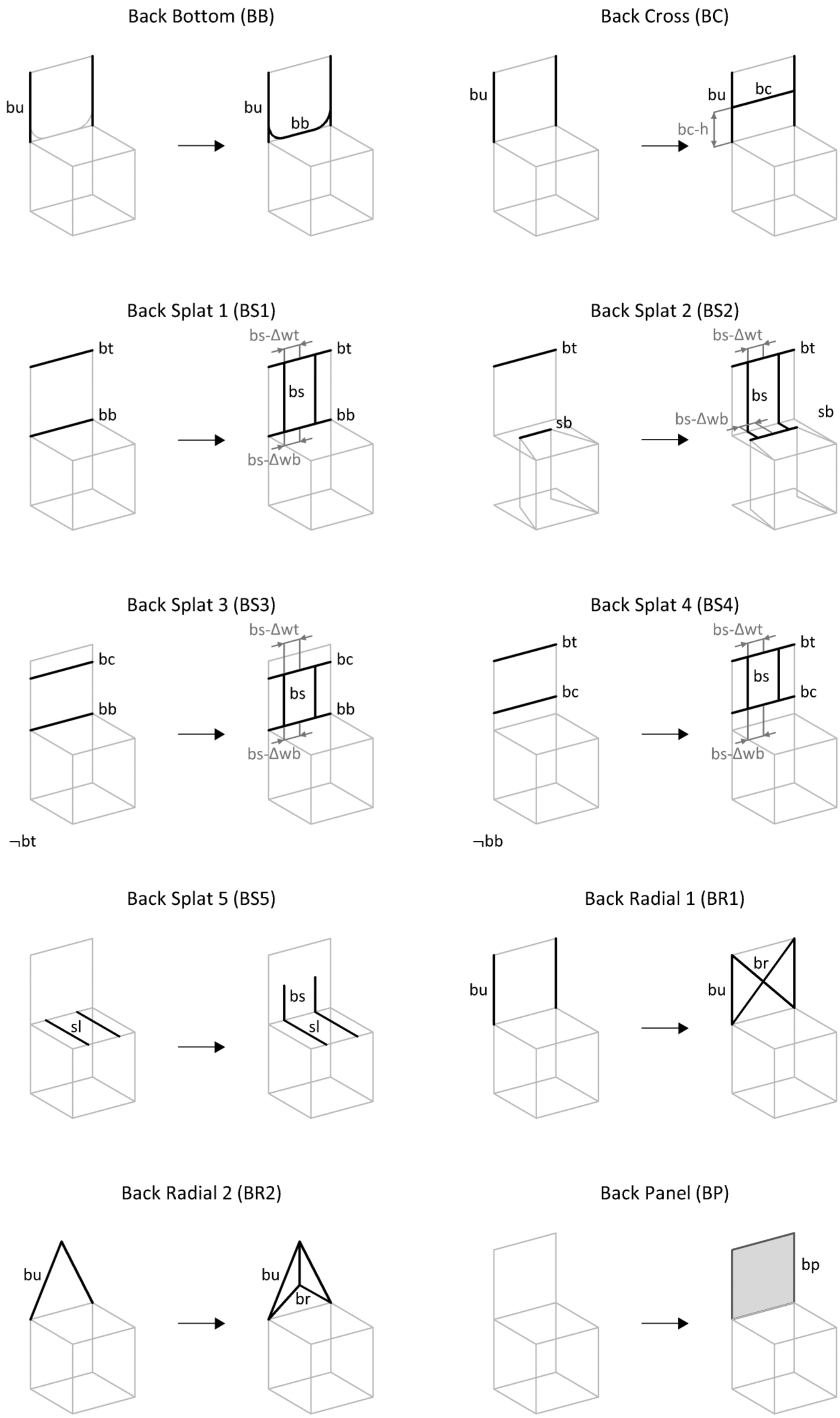


Fig. 5.8 Back rules schemata (2/2)

Table 5.4 Back rule parameters

Back Guides (BG)

Parameter	ID	Unit	Range	Def.
Height	bg-h	mm	[330,635]	483
Height Spacing	bg-Δh	mm	[0,200]	0
Back-Seat Angle	bg-α	°	[90,105]	90
Top Radius	bg-rt	%	[0,100]	0
Bottom Radius	bg-rb	%	[0,100]	0
Width	bg-w	%	[0,100]	50
Taper Width	bg-Δtw	%	[-100,100]	0

Back Upright 1-3 (BU1-3)

Parameter	ID	Unit	Range	Def.
Height	bu-h	%	[1,100]	100

Back Cross (BC)

Parameter	ID	Unit	Range	Def.
Height	bc-h	%	[1,99]	50

Back Splat 1-4 (BS1-4)

Parameter	ID	Unit	Range	Def.
Width Top Spacing	bs-Δwt	%	[0,100]	50
Width Bottom Spacing	bs-Δwb	%	[0,100]	50

Leg-Stretchers

The Leg-Stretchers rule set contains 18 rules, which are illustrated in **Fig. 5.9** and **Fig. 5.10**, and 9 parameters, illustrated in **Table 5.5**. The Leg-Stretchers rules can be divided into four groups: (1) guides (Leg-Stretchers Guides); (2) outer frame (Leg-Stretchers Front, Back and Side); (3) inner frame (Leg-Stretchers Cross, Long and Radial); and (4) panels (Leg-Stretchers Panel).

(1) The Leg-Stretchers Guides rule (**LSG**) parameters dictate its position (Height and Tilt Angle) and corners radii (Front and Rear). The Height controls the position of the plane in the Leg Front, ranging between the bottom endpoint (0%) and the top endpoint (100%) of the leg. The Tilt Angle controls the position of the plane in the Leg Back in relation to the Height (0%), ranging between the bottom endpoint (-100%) and the top endpoint (100%) of the leg.

(2) The Leg-Stretchers Front and Back configurations are defined by their position. If the Height of the rails is 0, the rails assume the guides shape (rules **LSF1** and **LSB1**); otherwise they linearly connect the legs (rules **LSF2** and **LSB2**). The Height parameter dictate the position of the rail, in relation to the Leg-Stretchers Guides plane (0%), and can range from the base plane (-100%) to the seat plane (100%). The Leg-Stretchers Side always assumes the shape of the guides, and may either connect linear legs (rule **LSS1**) or panelled legs (rules **LSS2** and **LSS3**).

(3) The Leg-Stretchers Cross and Long rules are identical to the Seat Cross and Long rules. The Leg-Stretchers Cross can connect the Leg-Stretchers Side or Long rails (rules **LSC1** and **LSC2**). The parameter Depth Spacing dictates the position of the rail, from nearly the stretchers front edge (1%) to nearly the stretchers back edge (99%). The Leg-Stretchers Long can connect the Leg-Stretchers Front with the Back or the Cross rails (rules **LSL1** and **LSL2**), the Leg-Stretchers Back with the Cross rails (rule **LSL3**), the Leg-Stretchers Front with the Leg Back (rule **LSL4**), or the Leg-Stretchers Back with the Leg Front (rule **LSL5**). The Width Front Spacing parameter dictates the position of the rail front endpoint in the front edge of stretchers,

and the Width Rear Spacing of the rail back endpoint in the back edge of the stretchers; both from the symmetry plane θ (0%) to the stretchers side edge (100%). The Leg-Stretchers Radial can assume a diagonal or central configuration (rules **LSR1** and **LSR2**), depending on the position of the legs at the stretchers plane.

(4) The Leg-Stretchers Panel outer shape is the same as the Leg-Stretchers Guides (rule **LSP**).

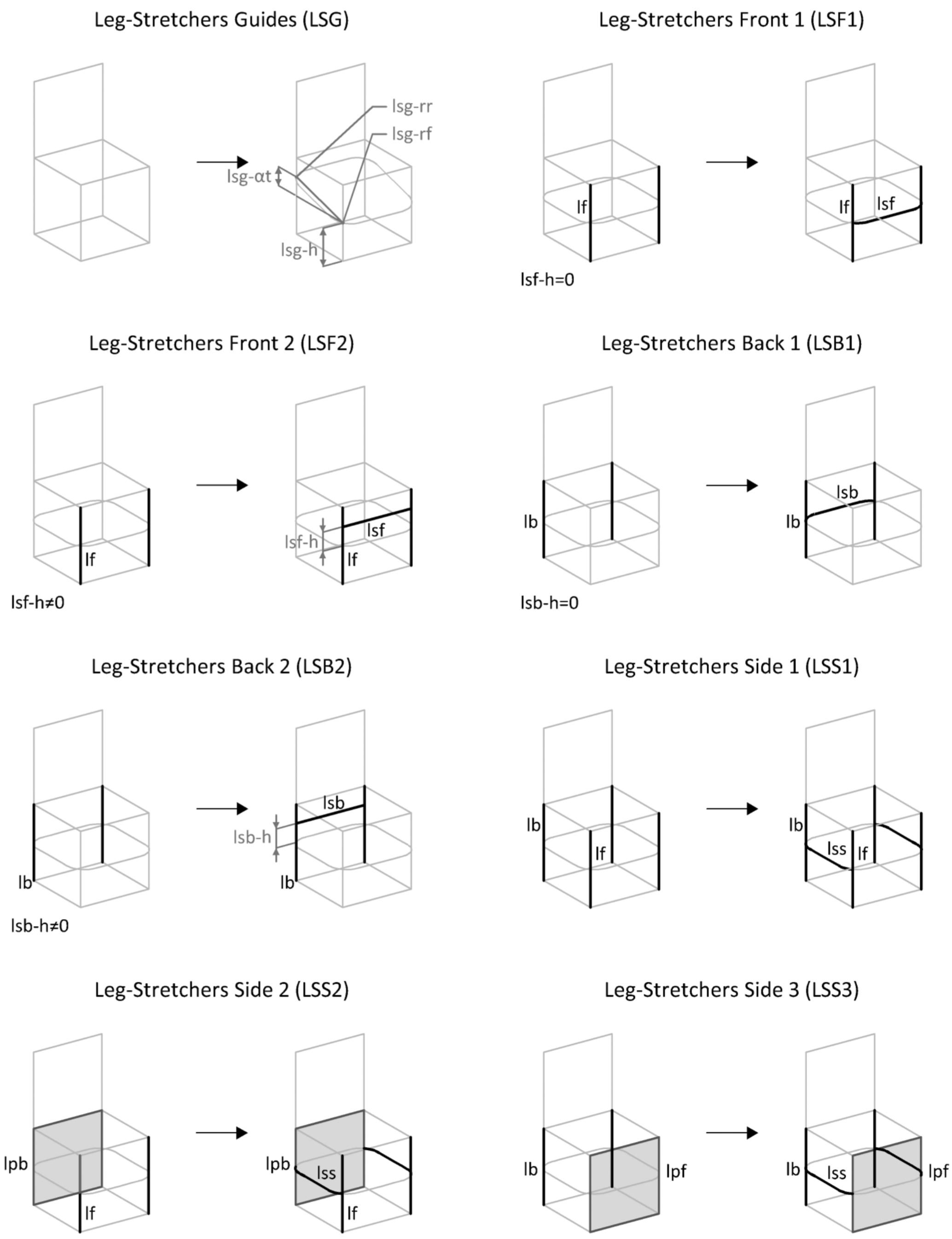


Fig. 5.9 Stretchers rules schemata (1/2)

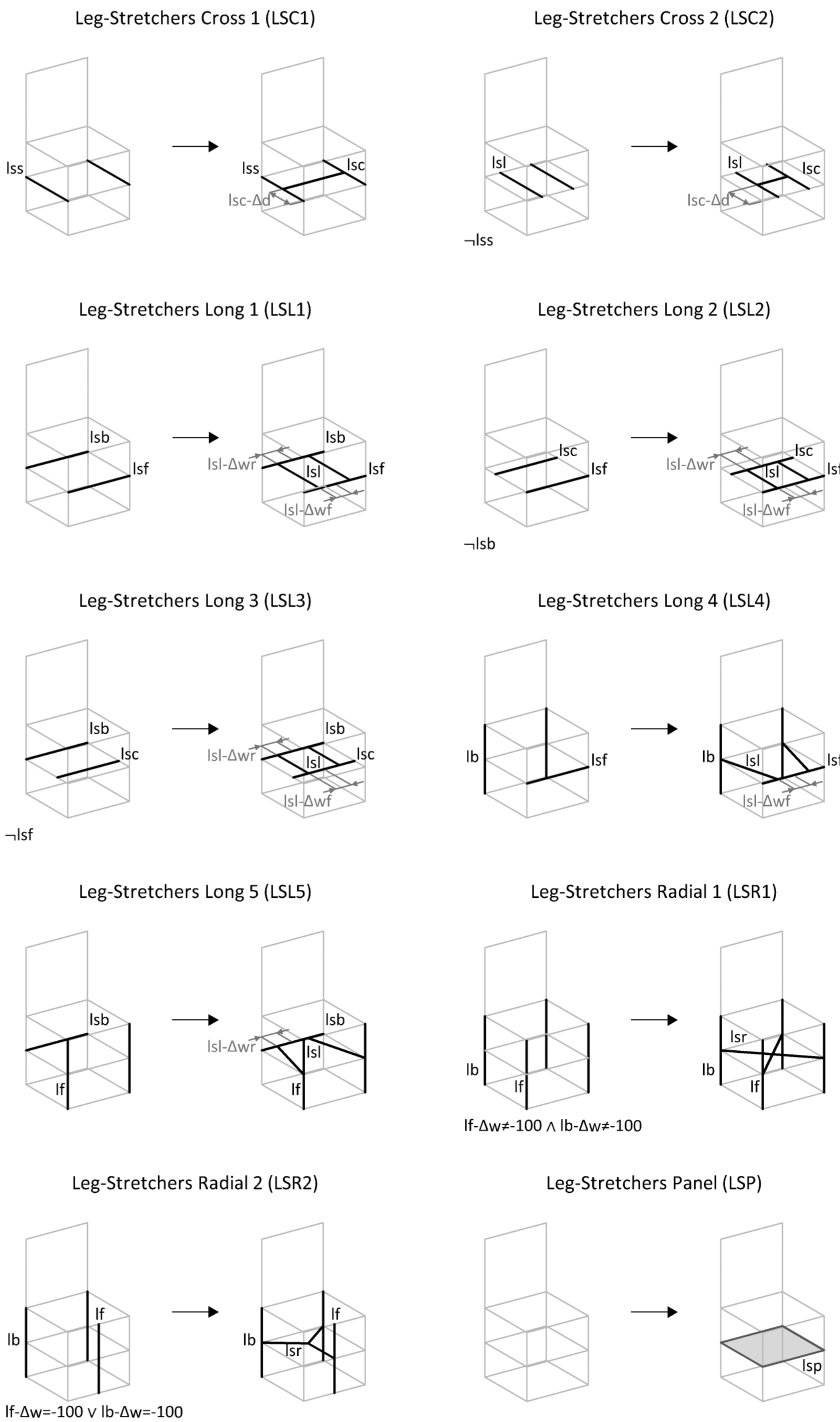


Fig. 5.10 Stretchers rules schemata (2/2)

Table 5.5 Stretchers rule parameters

Leg-Stretchers Guides (LSG)

Parameter	ID	Unit	Range	Def.
Height	lsg-h	%	[1,99]	50
Tilt Angle	lsg-αt	%	[-100,100]	0
Front Radius	lsg-rf	%	[0,100]	0
Rear Radius	lsg-rr	%	[0,100]	0

Leg-Stretchers Front 2 (LSF2)

Parameter	ID	Unit	Range	Def.
Height	lsf-h	%	[-100,100]	0

Leg-Stretchers Back 2 (LSB2)

Parameter	ID	Unit	Range	Def.
Height	lsb-h	%	[-100,100]	0

Leg-Stretchers Cross 1-2 (LSC1-2)

Parameter	ID	Unit	Range	Def.
Depth Spacing	lsc-Δd	%	[1,99]	50

Leg-Stretchers Long 1-5 (LSL1-5)

Parameter	ID	Unit	Range	Def.
Width Front Spacing	lsl-Δwf	%	[0,100]	50
Width Rear Spacing	lsl-Δwr	%	[0,100]	50

Leg-Base

The Leg-Base rule set contains 22 rules, which are illustrated in **Fig. 5.11**, **Fig. 5.12** and **Fig. 5.13**, and 8 parameters, illustrated in **Table 5.6**. The Leg-Base rules can be divided into four groups: (1) guides (Leg-Base Guides); (2) outer frame (Leg-Base Front, Back and Side); (3) inner frame (Leg-Base Cross, Long and Radial); and (4) panels (Leg-Base Panel).

(1) The Leg-Base Guides rule (**LBG**) parameters dictate its size (Width and Depth) and corners radii (Front and Rear). The Width is relative to the Seat Width, from the same (100%) to the minimum possible (1%). The Depth is relative to the distance between the horizontal projections, in the symmetry plane θ, of the seat front border and the back top border, from the same (100%) to the minimum possible (1%). The centre of the Base is not vertically aligned to the centre of the Seat (when the Back is tilted), as observed in the chairs of the sample (e.g. **S33**); the alignment of the Base is related to the centre of mass of the sitter's body.

(2) The Leg-Base Front, Back and Side are defined by the position of the bottom endpoints of the legs. If the bottom endpoint of the Leg Front (LBPF) lies in the Leg-Base Guides or is coincident to the centre point of the base (LBC), with the Leg Front or Leg-Base Side placed, the Leg-Base Front assumes the guides shape (rules **LBF1** and **LBF3**); otherwise it linearly connects the bottom endpoints of the Leg Front (rule **LBF2**). Analogously, if the bottom endpoint of the Leg Back (LBPB) lies in the Leg-Base Guides or is coincident with LBC, with the Leg Back or the Leg-Base Side placed, the Leg-Base Back assumes the guides shape (rules **LBB1** and **LBB3**); otherwise it linearly connects the bottom endpoints of the Leg Back (rule **LBB2**). If both LBPF and LBPB lie in the Leg-Base Guides or are coincident with LBC, with the Leg Front or Leg Back placed, the Leg-Base Side assumes the guides shape (rules **LBS1** and **LBS2**); otherwise it places a linear rail from the front or back legs (rules **LBS3** and **LBS4**).

(3) The Leg-Base Cross and Long rules are identical to the Seat Cross and Long rules. The Leg-Base Cross can connect the Leg-Base Side or Long rails (rules **LBC1** and **LBC2**). The parameter Depth Spacing dictates the position of the rail, from nearly the base front edge (1%) to nearly the base back edge (99%). The Leg-Base Long can connect the Leg-Base Front with the Back or the Cross rails (rules **LBL1** and **LBL2**), the Leg-Base Back with the Cross rails (rule **LBL3**), the Leg-Base Front with the Leg Back (rule **LBL4**), or the Leg-Base Back with the Leg Front (rule **LBL5**). The Width Front Spacing parameter dictates the position of the rail front endpoint in the front edge of base, and the Width Rear Spacing of the rail back endpoint in the back edge of the base; both from the symmetry plane θ (0%) to the base side edge (100%). The Leg-Base Radial rule is identical to the Seat Radial rule; the rail can assume a diagonal, central or star configuration (rules **LBR1**, **LBR2** and **LBR3**), depending on the position of the bottom endpoints of the legs. The parameter indicates the number of rails (between 3 and 5), for the star configuration.

(4) The Leg-Base Panel outer shape is the same as the Leg-Base Guides (rule **LBP**).

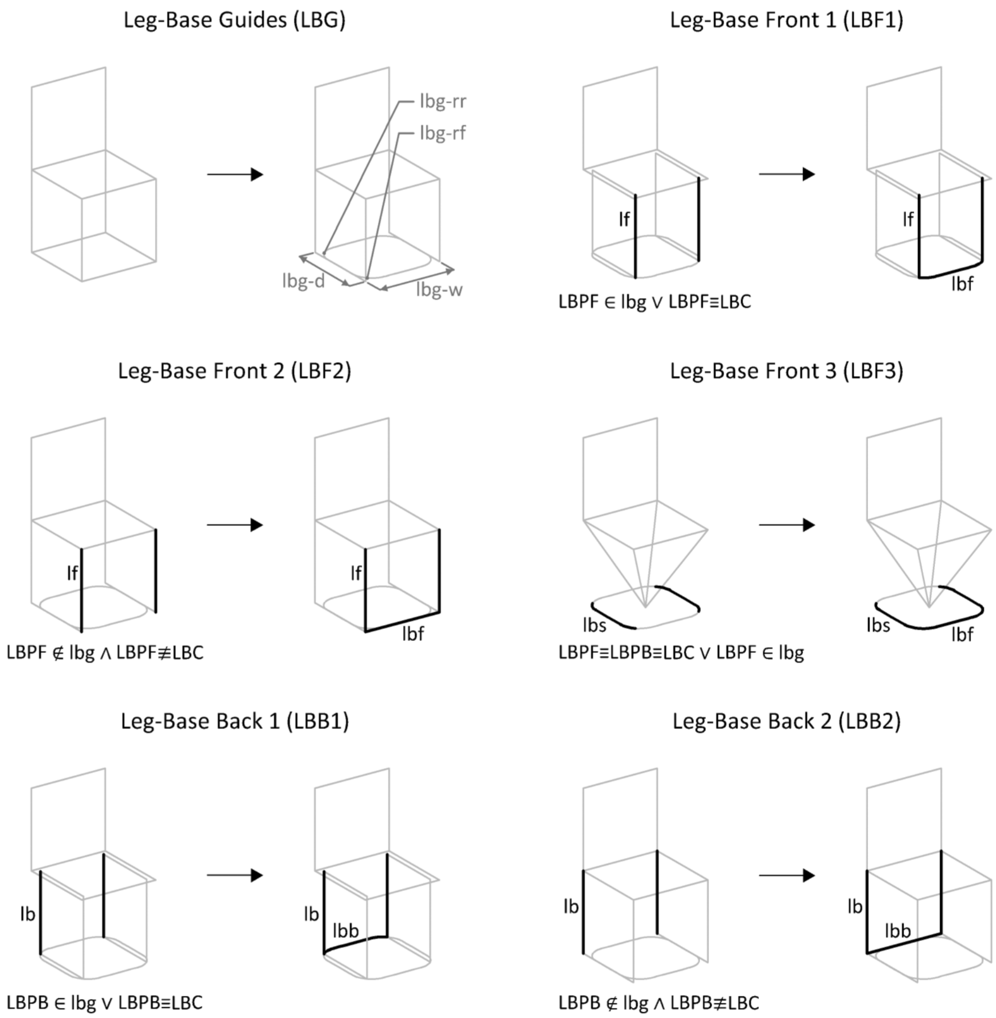


Fig. 5.11 Base rules schemata (1/3)

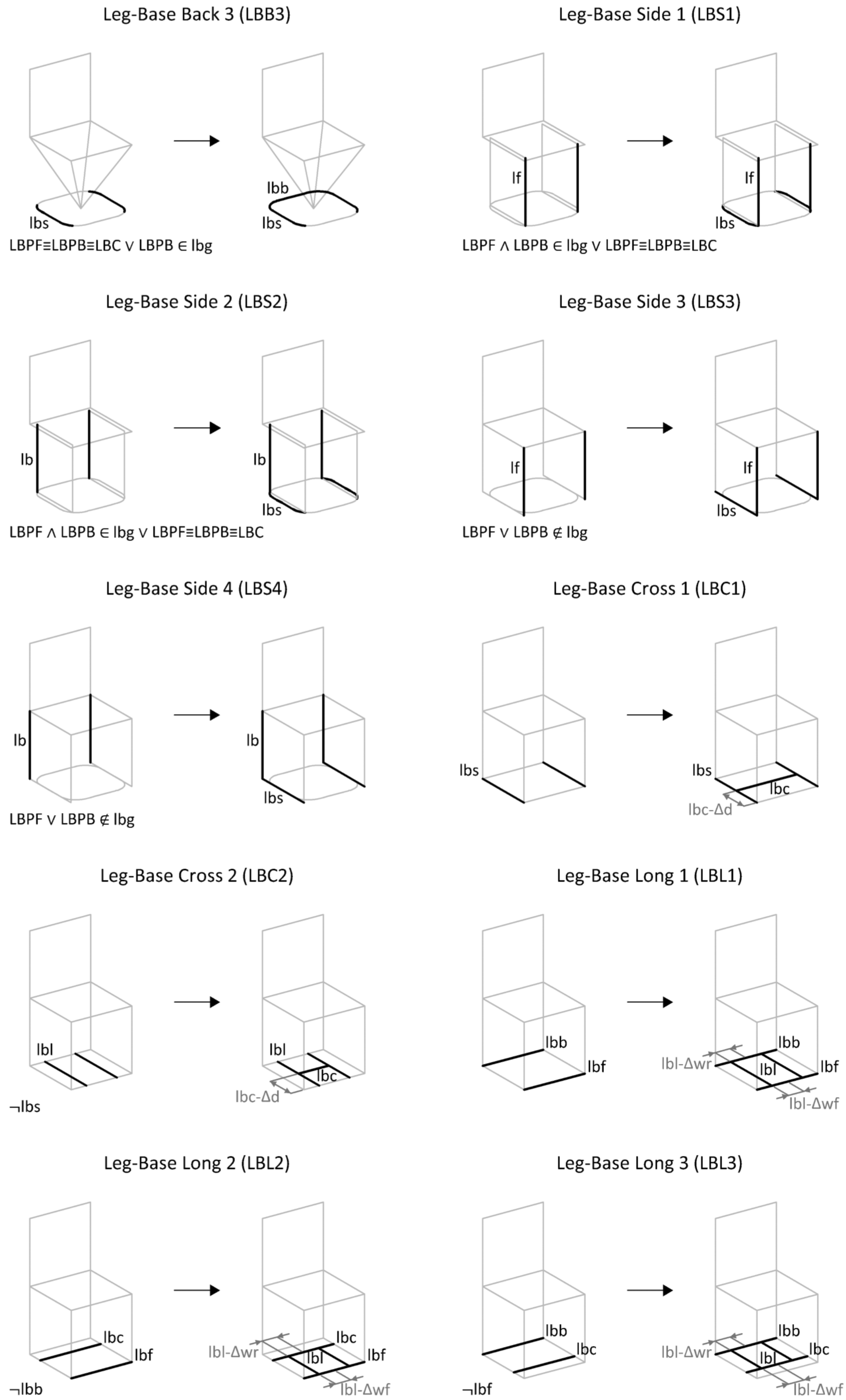


Fig. 5.12 Base rules schemata (2/3)

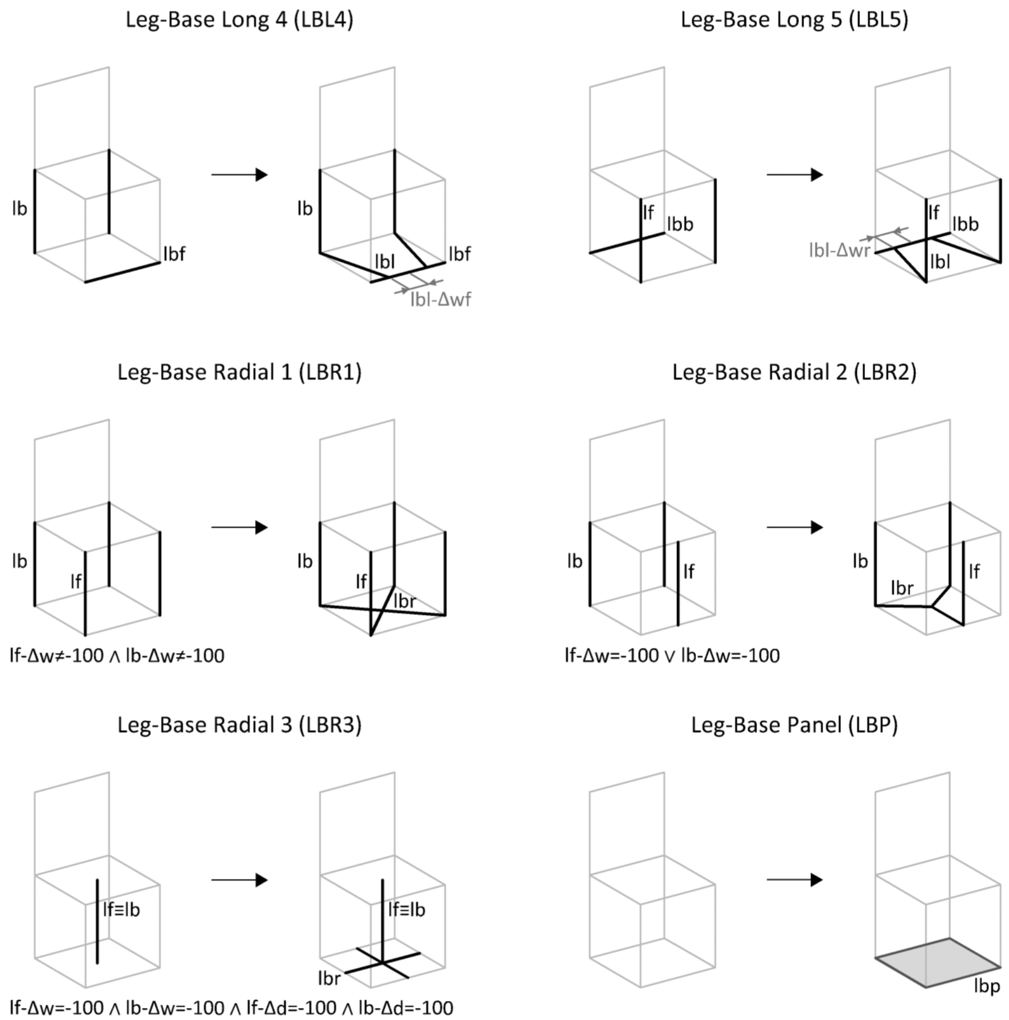


Fig. 5.13 Base rules schemata (3/3)

Table 5.6 Base rule parameters

Leg-Base Guides (LBG)

Parameter	ID	Unit	Range	Def.
Width	lbg-w	%	[1,100]	100
Depth	lbg-d	%	[1,100]	100
Front Radius	lbg-rf	%	[0,100]	0
Rear Radius	lbg-rr	%	[0,100]	0

Leg-Base Cross 1-2 (LBC1-2)

Parameter	ID	Unit	Range	Def.
Depth Spacing	lbc-Δd	%	[1,99]	50

Leg-Base Long 1-5 (LBL1-5)

Parameter	ID	Unit	Range	Def.
Width Front Spacing	lbl-Δwf	%	[0,100]	50
Width Rear Spacing	lbl-Δwr	%	[0,100]	50

Leg-Base Radial 3 (LBR3)

Parameter	ID	Unit	Range	Def.
Number	lbr-n	N/A	[3,5]	4

Arms

The Arms rule set contains 18 rules, which are illustrated in **Fig. 5.14** and **Fig. 5.15**, and 8 parameters, illustrated in **Table 5.7.** The Arms rules can be divided into four groups: (1) guides (Arm Guides); (2) outer frame (Arm Support Front, Arm Support Back and Armrest); (3) inner frame (Arm Support Side); and (4) panels (Arm Panel).

(1) The Arm Guides rule (**AG**) parameters dictate its size (Height and Depth), position (Depth Rear Spacing), corners radii (Front and Rear) and Tilt Angle. The values of Height (maximum and minimum), Arms Depth (minimum) and Arms Depth Spacing (maximum) parameters are related to anthropometric standards. The Arms Depth can range between 245 mm (0%) to the same dimension of the Seat Depth (100%). The Arms Depth Spacing can range between zero and 100 mm. The Tilt Angle is the dimension of the arms back edge in relation to the arms front edge; it can range from equal (0%) to zero (100%) to the double (-100%).

(2) The Arm Support Front can be an extension of (i) the Seat Side or the (ii) Leg Front. (i) If the top endpoint of the Leg Front (SPF) lies in the Seat Guides, the Arm Support Front assumes the guides shape (rule **ASF1**); otherwise it linearly connects the front endpoint of the Seat Side with the arms front corners (rule **ASF2**). (ii) If the front leg is located in the side plane, the Arm Support Front connects SPF with the front endpoint of the Armrest (rule **ASF3**); otherwise it connects SPF with the arm front corners (rule **ASF4**). Similarly, the Arm Support Back can be an extension of (i) the Seat Side or (ii) the Leg Back. (i) If the top endpoint of the Leg Back (SPB) lies in the Seat Guides, the Arm Support Back assumes the guides shape (rule **ASB1**); otherwise it linearly connects the back endpoint of the Seat Side with the arms back corners (rule **ASB2**). (ii) If the back leg is located in the side plane, the Arm Support Back connects SPB with the back endpoint of the Armrest (rule **ASB3**); if the back leg is located in the back plane, the Arm Support Back is an upright extension of the Leg Back (rule **ASB4**); otherwise it connects SPB with the arm back corners (rule **ASB5**). The Armrest may be placed from the Arm Support Side (rule **AR1**), the Arm Support Front (rule **AR2**), the Arm Support Back (rule **AR3**), or the Arms Panel (rule **AR4**).

(3) The Arm Support Side connects the top edge of the arms with the Seat Side (rule **ASS1**), the Leg Front (rule **ASS2**), or the Leg Back (rule **ASS3**). The Depth Top Spacing parameter dictates the position of the rail top endpoint in the top edge of arms, and the Depth Bottom Spacing of the rail bottom endpoint in the bottom edge of arms; both from the front (0%) to the back (100%) arms edges.

(4) The Arm Panel outer shape is the same as the Arm Guides (rule **AP**).

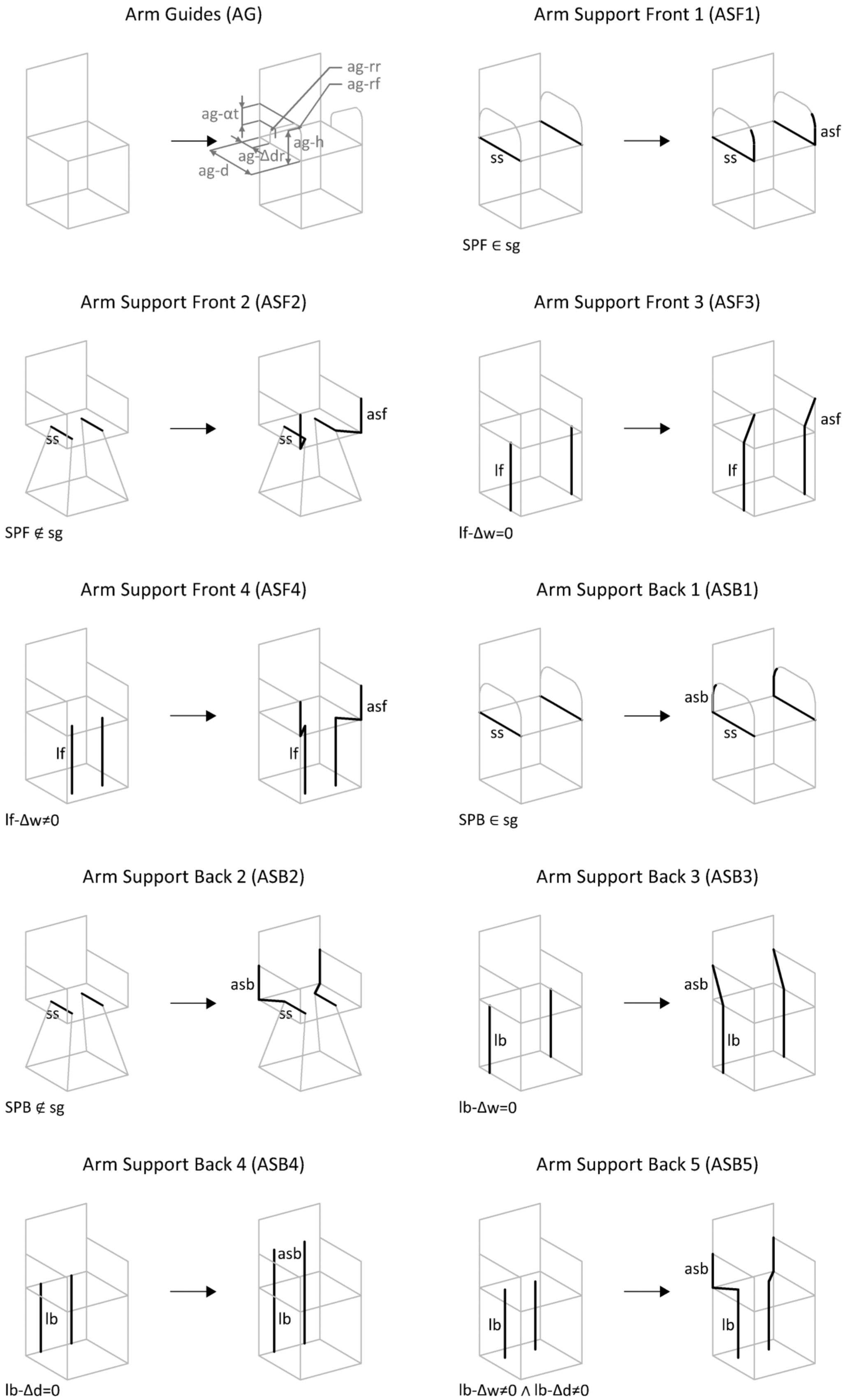


Fig. 5.14 Arms rules schemata (1/2)

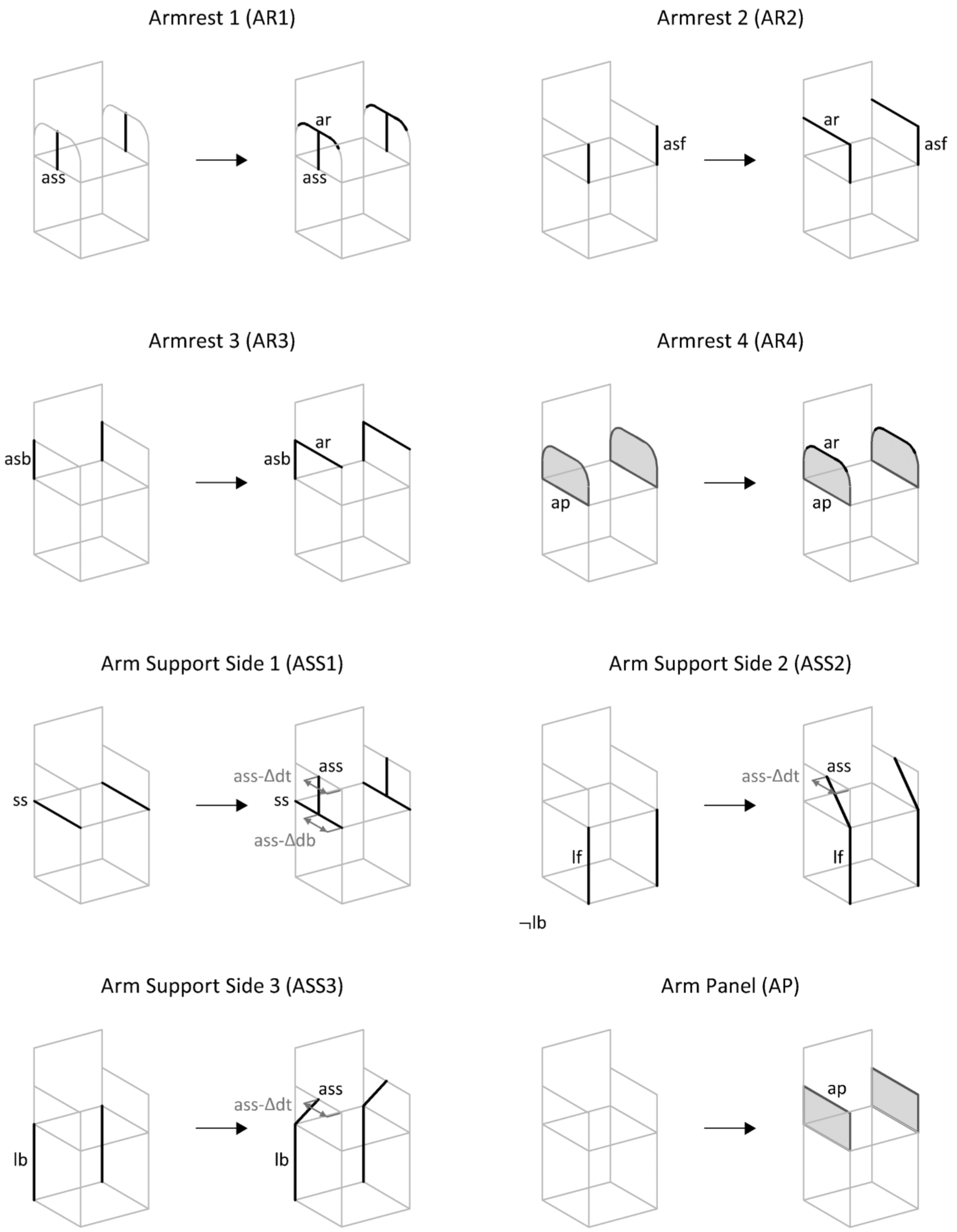


Fig. 5.15 Arms rules schemata (2/2)

Table 5.7 Arms rule parameters

Arm Guides (AG)

Parameter	ID	Unit	Range	Def.
Height	ag-h	mm	[191,254]	223
Depth	ag-d	%	[0,100]	100
Depth Rear Spacing	ag-Δdr	mm	[0,100]	0
Tilt Angle	ag-αt	%	[-100,100]	0
Front Radius	ag-rf	%	[0,100]	0
Rear Radius	ag-rr	%	[0,100]	0

Arm Support Side 1-3 (ASS1-3)

Parameter	ID	Unit	Range	Def.
Depth Top Spacing	ass-Δdt	%	[0,100]	50
Depth Bottom Spacing	ass-Δdb	%	[0,100]	50

Solid Mode

The Solid Mode rule set contains 3 rules, illustrated in **Fig. 5.16**, and 6 parameters, illustrated in **Table 5.8**. The rules can be divided into two groups: (1) frame (Mode-Solid Frame Section Round and Mode-Solid Frame Section Square) and (2) panels (Mode-Solid Section Panels).

(1) The solid frame rules thicken the wireframe frame (generated by the previous rules), using a round section (rule **MSF-SR**), constrained by the Diameter, or a square section (rule **MSF-SS**), constrained by the Width and Length. The section can have a maximum dimension of 280 mm, considering the case of two legs that cover the maximum size of the seat (Seat Width of 560 mm). The Taper Ratio parameter is only applicable to the Leg Front and the Leg Back. It corresponds to the dimension of the bottom section in relation to the top section; it can range from equal (100%) to the minimum possible (1%), i.e., from a straight leg to a pyramidal leg.

(2) The solid panel rule (**MSP**) thickens the wireframe panels (generated by the previous rules). The rule is constrained by the Thickness parameter (ranging from 1 to 100 mm).

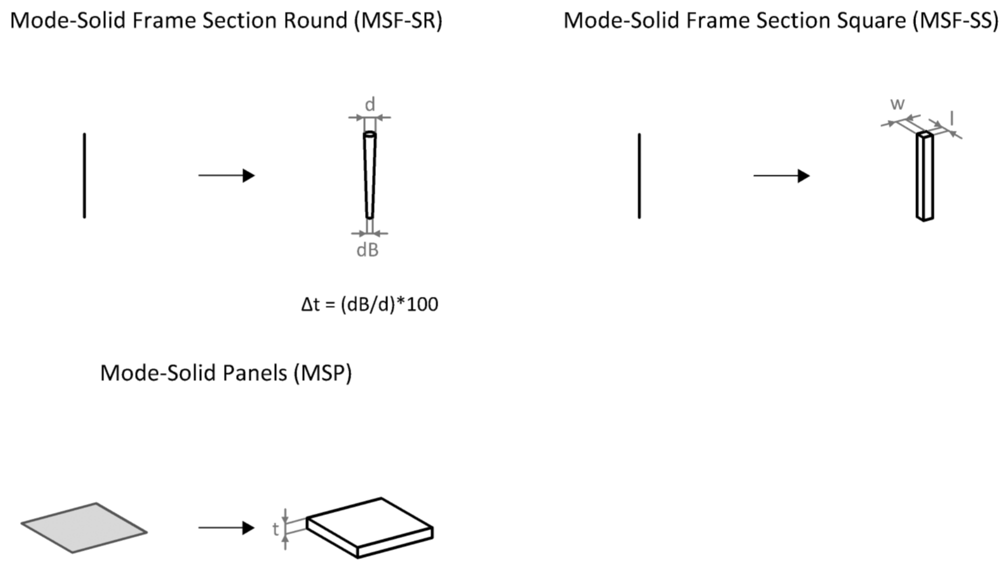


Fig. 5.16 Solid Mode rules schemata

Table 5.8 Solid Mode rule parameters

Mode-Solid Frame Section Round (MSF-SR)

Parameter	ID	Unit	Range	Def.
Diameter	msf-srd	mm	[1,280]	30
Taper Ratio*	msf-Δt	%	[1,100]	100

* Only for lf ∧ lb

Mode-Solid Frame Section Square (MSF-SS)

Parameter	ID	Unit	Range	Def.
Width	msf-ssw	mm	[1,280]	30
Length	msf-ssl	mm	[1,280]	30
Taper Ratio*	msf-Δt	%	[1,100]	100

* Only for lf ∧ lb

Mode-Solid Panels (MSP)

Parameter	ID	Unit	Range	Def.
Thickness	msp-t	mm	[1,100]	10

Termination

The termination rule (**T**) is illustrated in **Fig. 5.17**. The rule erases the guides introduced in the initial shape, ensuring that, after applying it, no rule of the grammar is applicable. Note that the guides may not have the configuration displayed in the figure (since the rules **LG**, **SG**, **BG**, and **LBG** may transform the initial shape into a parameterized shape). This rule also guarantees that every final design has the mandatory parts of a chair (as mentioned in the **Multipurpose Chair Ontology**): Legs, Seat, and Back. As such, the for the termination rule to be applied there must be at least: (1) one leg (Leg Front, Leg Back, Leg Panel Front, Leg Panel Back, Leg Panel Side, or Leg Panel Radial), (2) one element in the inner seat (Seat Panel, Seat Cross or Seat Long), and (3) one element in the inner back (Back Panel, Back Top or Back Cross).

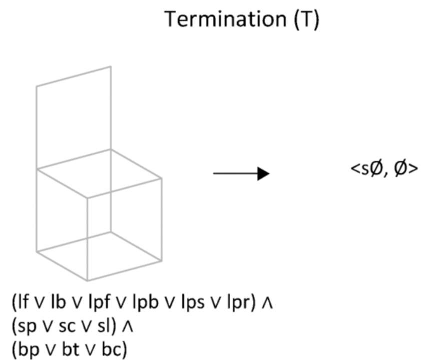


Fig. 5.17 Termination rule schemata

Other Rules

There are other rules which were not included in the Version 1.2 of the MCG, but were part of previous versions. These extra rules refer to the detail rule set. In earlier versions, the shape detail comprised a higher level, and the solution space was more restricted (particularly in the first two versions). There are five detail rules, which can be consulted in **Appendix 5.A.1**.

5.3 Meta-Grammar

The Meta-Grammar is a generalization of the MCG. The grammar contains 35 meta-rules, which are generalizations of rules; each meta-rule can be applied to one or more of the 104 MCG rules (excluding the Solid Mode and Termination rule sets). The meta-rules comprise more abstract shapes than the MCG rules, whose shapes include a semantics associated to multipurpose chairs. The Meta-Grammar is based on the Meta-Ontology described in the previous chapter (**Multipurpose Chair Ontology**). The purpose of the Meta-Grammar was to support the development of the MCG, by ensuring its overall coherence and completeness. The meta-grammar also simplified the implementation; 19 meta-rules were implemented to avoid duplication.

Meta-rules result from a generalization process, i.e., the inference of a general rule from more particular rules. When two or more rules exhibit a similar pattern, it can be generalized in a more abstract meta-rule. **Fig. 5.18** exemplifies the process, where two rules (Seat Panel and Back Panel) were generalized into a meta-rule (Panel). The meta-rules are illustrated in **Appendix 5.B.1**, and the correspondence between meta-rules and rules is displayed in **Appendix 5.B.2**.

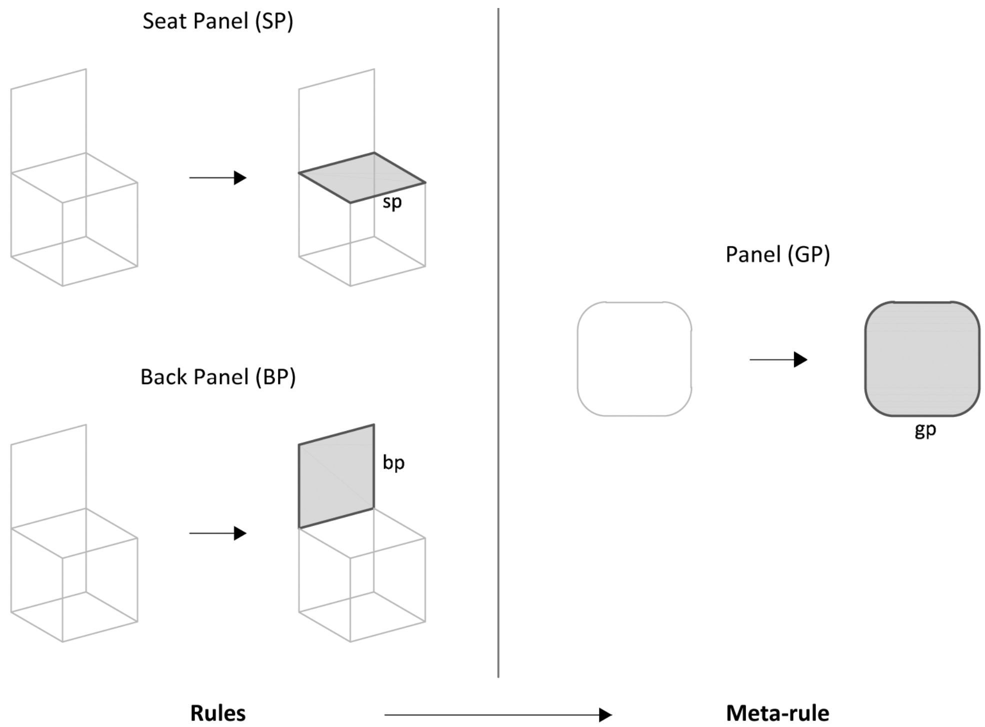


Fig. 5.18 Process for developing meta-rules: generalization of two rules (left) to one meta-rule (right)

5.4 Sub-Grammars

This section presents seven sub-grammars generated by the MCG. The generic MCG is able to generate four types of grammars: specific grammars (DCG, JCG, TCG, and ICG), common grammars (DJCG), hybrid grammars (DJHG), and complement grammars (SCG). The distinctive grammars will not be discussed, since they cannot generate complete designs. **Appendix 5.C.1** discriminates the rules and parameters for each of the seven grammars. The grammars comprised different generation methods, which will be discussed below.

5.4.1 Specific Grammars

This section details a method for generating specific grammars and a method for adapting a specific grammar to another grammar. These methods were applied in the generation of the four specific grammars mentioned above.

Method 1: generating a specific SG from a generic SG

The method requires a set of designs that share the same sub-language and are generated by a generic SG. Each design uses or not a given generic SG rule and assigns a value to a given generic SG parameter. The specific SG will be defined by three types of rules and three types of parameters, obtained by restricting the generic SG rules and parameters. Each type has a corresponding ID (displayed in parenthesis):

1) O*ptional rule* (VX): if some designs use a generic SG rule, the specific SG includes the rule and it can or not be used;
2) *Mandatory rule* (VV): if all the designs use a generic SG rule, the specific SG includes the rule but it has to be mandatorily used;
3) *Deleted rule* (XX): if no design uses a generic SG rule, the specific SG does not include the rule;
4) *Optional parameter* ([*a,b*]): if the designs use at least two different values in a given generic SG parameter, the specific SG parameter is the range [*a,b*], being *a* the lower value used by the designs and *b* the higher value used by the designs; [1]
5) *Mandatory parameter* (*a*): if all the designs use a value *a* and *a* is different from the default value, the specific SG parameter is restricted to the value *a*;
6) *Deleted parameter* (N/A): if all the designs use the default value, the specific SG does not apply that parameter.

This method was employed in the generation of the DCG, JCG and ICG from the MCG (version 1.2), using the designs of the corpus. Note that the DCG, JCG and ICG were part of the corpus of the MCG in earlier versions (respectively, versions 0.1, 0.2 and 1.1).

Method 2: incorporating an existing specific SG into a generic SG

The method requires a specific SG whose language is a sub-language of the generic SG language. The process of incorporating a specific SG into a generic SG comprises three main steps: (1) *comparison* (of both grammars), (2) *selection* (of rules and parameters of the specific SG applicable to the generic SG), and (3) *conversion* (of the notation used in the specific SG to the one used in the generic SG).

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[1] The methodology could be extended to consider other types of parametric restrictions; for e.g. if the designs only use two different values (*a* and *b*), the specific parameter would be the set {*a*,*b*}.

This method was applied to the incorporation of the TCG, developed by Barros, Duarte & Chaparro (2011), into the MCG. The step 1 of the incorporation process regarded the following topics: (1) *type*: both are parametric set grammars from the analytic type; (2) *corpus*: one design is common to both corpuses (**214** chair); (3) *shape representation:* both represent designs by the wireframe skeleton, which is converted to a solid shape afterwards (in the case of TCG, only in the implementation); (4) *shape abstraction*: curves are abstracted to lines and arcs in MCG, while in TCG are abstracted to lines (and converted to NURBS in the implementation); (5) *dimensional space*: is 3D in MCG and 2D (front view) in TCG; (6) *initial shape:* in MCG it represents the bounding box of the chair, while in TCG it depicts the back outer frame; (7) *rules*: both comprise rules which add chair parts, but MCG rules address all chair parts, while TCG rules address the backrest inner frame parts. The TCG rules comprise a higher level of shape detail; (8) *parameters*: the units in TCG are fractions, while in MCG are millimetres, degrees and percentages. The TCG does not indicate default values, unlike MCG.

The step 2 of the incorporation process comprised the selection of four rules and four parameters of the TCG, and step 3 required the conversion of units. Steps 2 and 3 are detailed in **Table 5.9**. The converted TCG also includes mandatory rules and parameters related to the other chair parts, obtained according to the method 1 previously described.

Table 5.9 Conversion of the original TCG to one readable by the MCG

	TCG (original)		TCG (in MCG)	
Rules	4		Back Splat	
	27		Back Bottom	
	28		Back Cross	
	29/30		Back Panel	
Parameters	a'	[1/8,3/8]	Back Splat Width Bottom Spacing (%)	[13,38]
	a’’	[1/2,1]	Back Splat Width Top Spacing (%)	[50,100]
	a’’’	[3/4,1]	Back Cross Height (%)	[75,99]
	b’’	[1/4,2/4]	Back Height Spacing (mm)	[101,200]

5.4.2 Common and Hybrid Grammars

This section details a method to generate common and hybrid grammars. The methods require *n* overlapping specific SG, i.e., grammars that have at least one rule in common. **Table 5.10** exemplifies some of the procedures, given two specific SGs (A and B).

Method 1: generating a common SG from overlapping specific SGs

The procedures to generate common SG rules are, considering a rule applicable to *n* specific SGs: (1) if the specific SGs use the same type of rule, the common SG rule is from that type; (2) if at least one specific SG uses a *deleted rule*, the common SG rule is a *deleted rule*; and (3) in the remaining cases, the common SG rule is an *optional rule*.

The procedures to generate common SG parameters are, considering a parameter applicable to *n* specific SGs: (1) if all the specific SGs use a *deleted parameter*, the common SG parameter is a *deleted parameter*; (2) if the intersection of the specific SGs parametric ranges is a value, the common SG parameter is that value; and (3) in the remaining cases, the common SG parameter is the range [*a*, *b*], being *a* the *n* smaller value and *b* the *n* larger value used by the specific SGs parametric ranges (*n* is the number of specific SGs). This is valid for intersecting intervals (the result is the intersection between them) and for non-intersecting intervals (the result is the interval between them).

Method 2: generating a hybrid SG from overlapping specific SGs

The procedures to generate hybrid SG rules are, considering a rule applicable to *n* specific SGs: (1) if the specific SGs use the same type of rule, the hybrid SG rule is from that type; and (2) in the remaining cases, the hybrid SG rule is an *optional rule*.

The procedures to generate hybrid SG parameters are, considering a parameter applicable to *n* specific SGs: (1) if all the specific SGs use a *deleted parameter*, the hybrid SG parameter is a *deleted parameter*; (2) if the union of the specific SGs parametric ranges is a value, the hybrid SG parameter is that value; and (3) in the remaining cases, the hybrid SG parameter is the range [*a*,*b*], being *a* the smallest value and *b* the largest value used by the specific SGs parametric ranges.

Table 5.10 Calculation of rules and parameters of a common SG and a hybrid SG

	Specific SG A	**Specific SG B**	**Common SG**	**Hybrid SG**
Rules	VV	VV	VV	VV
	VX	VX	VX	VX
	XX	XX	XX	XX
	VV	VX	VX	VX
	VV	XX	XX	VX
	VX	XX	XX	VX
Parameters	$[a_1,a_2]$	$[b_1,b_2]$, $b_1 \leq a_2 \wedge b_2 \geq a_1$	$[a_1,a_2] \cap [b_1,b_2]$	$[a_1,a_2] \cup [b_1,b_2]$
	a	b	[a,b]	[a,b]
	a	[a,b]	a	[a,b]
	N/A	N/A	N/A	N/A

This procedure was applied to create the common grammar DJCG and the hybrid grammar DJHG, resulting from the overlapping of the DCG and the JCG specific grammars.

5.4.3 Complement Grammar

The SCG contains the synthetic rules of the MCG, which are not used by the DCG, JCG, TCG and ICG. Instead of being derived from the analysis of designs, synthetic rules result from synthetic processes, i.e., from new combinations of the elements of the vocabulary. A synthetic rule is not applicable in the reproduction of any design of the corpus, but it can be (or not) found in other existing designs. The SCG contains 41 rules, meaning that 38% of the MCG rules were not derived from corpus analysis.

Several synthetic processes can be employed, for instance: (i) new arrangements of the vocabulary elements; (ii) analogy of a synthetic rule from an analytic rule, and (ii) deduction of a synthetic rule from a general meta-rule (being the Meta-Grammar a source for generating many synthetic rules). The Stretchers Panel (**Fig. 5.10**) is an example of a synthetic rule. It can be inferred by analogy from the Seat Panel rule (**Fig. 5.6**): if a panel can be added from the Seat Guides, then a panel can be added from the Stretchers Guides. Note that both rules are particular cases of the Panel rule (Fig**. 5.18**).

The SCG is not a valid grammar, since it cannot generate complete designs. Nevertheless, the SCG is useful to reveal rarely used rules and parameters, which can be a driver for exploration or an indication for further refinements of the MCG.

5.5 Designs

The various grammars included in the MCG can generate three types of designs: corpus designs, existing designs, and new designs. **Fig. 5.19** illustrates eight designs generated by the DCG. The Solid Mode rules are not displayed, for clarity (these can be observed in the next chapter, **The ChairDNA Design Tool**).

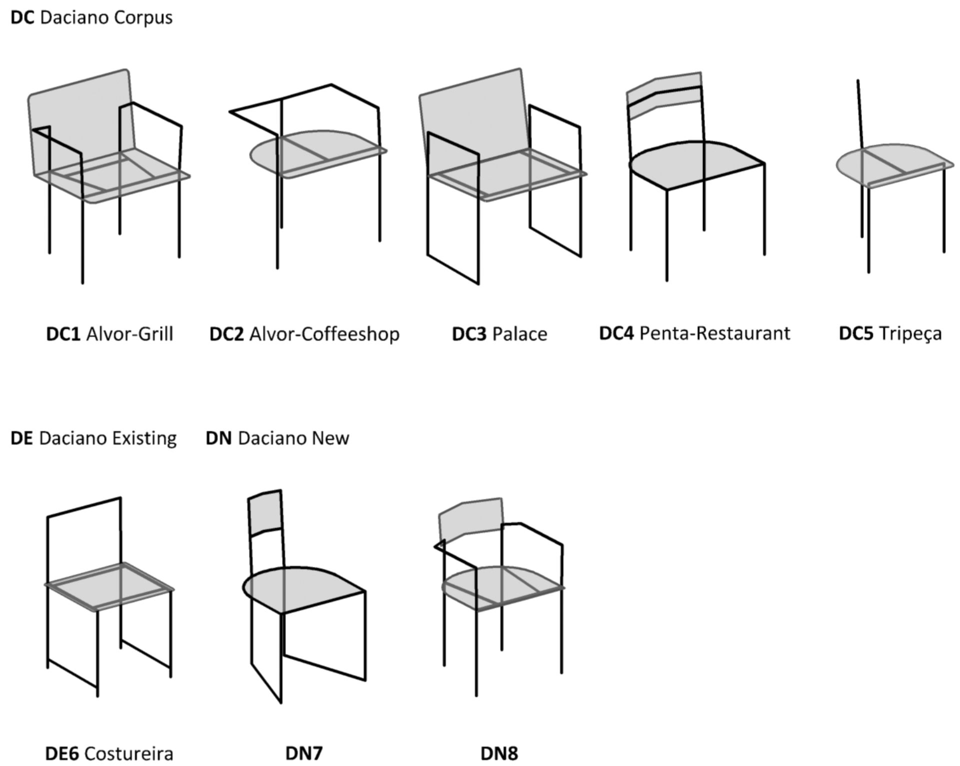

Fig. 5.19 Designs generated by the DCG

Designs generated by the JCG are displayed in **Appendix 5.D.1**; designs generated by the DJCG and DJHG are illustrated in **Appendix 5.D.2**, designs generated by the TCG are shown in **Appendix 5.D.3** and designs generated by the ICG are available in **Appendix 5.D.4**.

5.5.1 Derivations

A derivation is the step-by-step generation of a design, from the initial shape to the final solution. In the MCG, the derivation corresponds to the successive addition of chair parts. The generation of a design must obey to a certain rule application sequence, although there remains a great freedom of choice in what rules to apply at a certain derivation step. The decision tree, showing the parts (nodes) and the network of choices (edges), is illustrated in the appendixes of the chapter **Multipurpose Chair Ontology**. At the beginning of the derivation (after the initial shape), all the Guides and Panels are available, as well as the Legs and the Seat Outer Frame. Therefore, the user may start by placing the Seat or the Legs, and then proceed to the other chair parts. Generically, the placement of the inner frame parts comes after the insertion of the outer frame. The method of progression was based on the analysis of the **Multipurpose Chair Sample**, not considering the designer's preferences; however a group of designers who used the implementation of the grammar considered the generation sequence appropriate (this is detailed in the chapter **User Evaluation of ChairDNA**). **Fig. 5.20** illustrates an example of a derivation of the **Tripeça** chair, which belongs to the corpus of the DCG grammar. Shape labels and Solid Mode rules are omitted, for clarity.

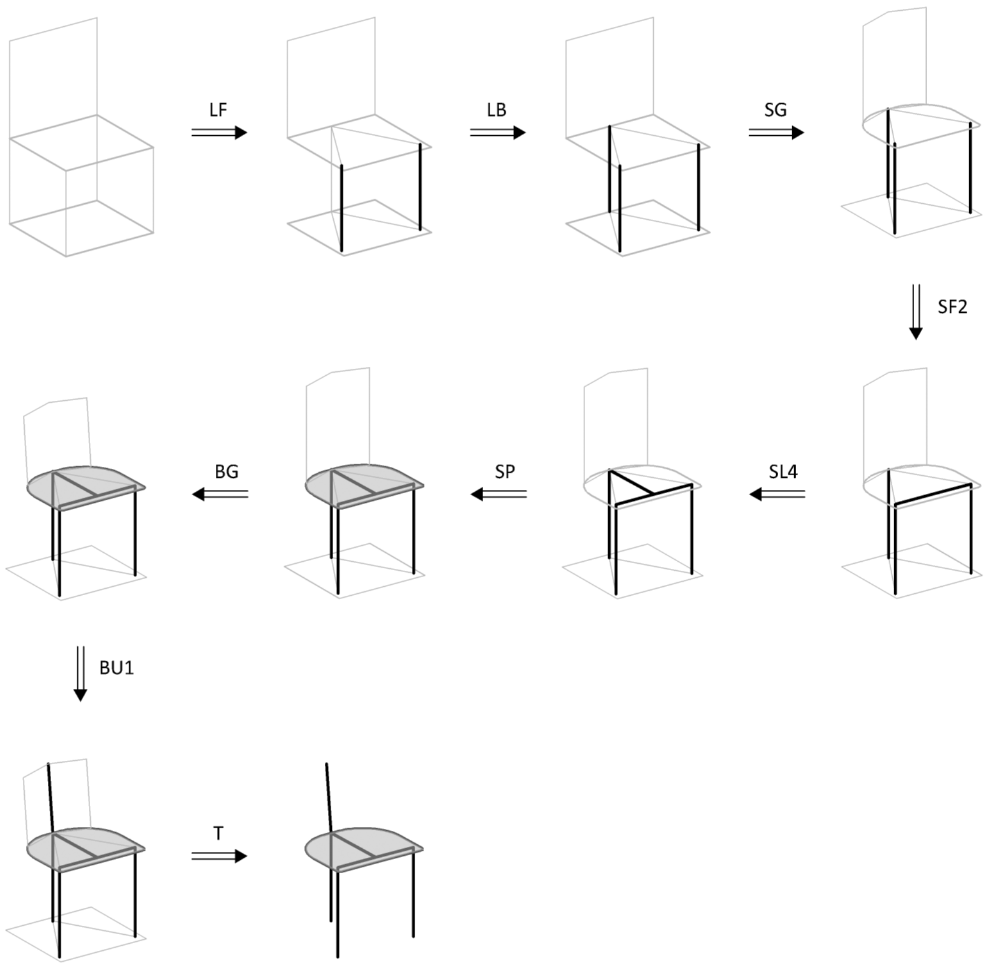

Fig. 5.20 Derivation of the Tripeça chair

5.6 Tests

Analytic specific SGs are able to generate three types of designs: corpus designs, existing designs, and new designs (Stiny & Mitchell 1978). Analogously, an analytic generic SG can generate three types of specific SGs: SGs from the corpus, existing SGs, and new SGs. The capabilities of a generic SG to generate specific SGs can be evaluated according to three tests:

1) *Descriptive test*: evaluates whether a generic SG is able to generate specific SGs from the corpus;
2) *Analytic test*: evaluates whether a generic SG is able to generate existing specific SGs that are not from the corpus but contemplate a sub-language of the generic SG language;
3) *Synthetic test*: evaluates whether a generic SG is able to generate new specific SGs.

The MCG successfully accomplished the three aforementioned tests: (1) the MCG is able to generate grammars from the corpus (DCG, JCG and ICG); (2) is able to accommodate some rules of an existing specific SG (TCG)[2]; and (3) is able to generate new grammars (DJCG and DJHG).

The capabilities of an analytic SG to generate designs can also be evaluated according to three tests (Stiny & Mitchell 1978):

1) *Descriptive test*: evaluates whether an SG is able to generate designs from the corpus;
2) *Analytic test*: evaluates whether an SG is able to generate existing designs that are not from the corpus but belong to the language;
3) *Synthetic test:* evaluates whether an SG is able to generate new designs that belong to the language.

The MCG accomplished the three tests, being able to generate (1) corpus designs, (2) existing designs and (3) new designs. The designs used in the first two tests are detailed in the chapter **Multipurpose Chair Sample.** The three tests were independently applied to the DCG, JCG, and TCG. The ICG was evaluated by the first two tests, and the DJCG and DJHG were evaluated through the third test.

The descriptive and analytic tests can be further refined, since an SG can only partially reproduce existing designs. The completeness test gives the extent to which a grammar can reproduce existing designs. This test was employed in the grammar implementation, and will be detailed in the next chapter (**The ChairDNA Design Tool**).

[2] Note that the original incorporation of the TCG (in version 1.1.1) required the addition of the Back Bottom rule and the Back Splat Width Top Spacing parameter.

5.7 Discussion

This chapter described the generic MCG and several sub-grammars of different types; namely, specific (DCG, JCG, TCG and ICG), common and hybrid grammars (DJCG and DJHG).

The MCG comprises three analytic specific grammars. The DCG and JCG characterize two individual designer's styles. Individual styles characterize the designs of one individual. The designs reveal formal coherence or a similar approach on handling domain-specific design tasks, and can be motivated by the designer's background, principles, motivations, and values (Chan 2000). A qualitative description of each style, made by the analysis of rules and parameters of each grammar, will be made in the next chapter (**The ChairDNA Design Tool**).

The MCG was derived from the DCG. There is a relation between the MCG design strategy and the design process of the designer Daciano da Costa. The designer's method comprised a composition of lines, surfaces and volumes, and his designs reveal and additive constructive process, where the components are fragmented and autonomous (Martins 2001). This method is also observed in the MCG. However, this relation was not intentional; it was verified *a posteriori*. This may indicate that the analysis of the designs of one individual may indicate *per se* clues of his design process. If the MCG considered in the beginning the analysis of designs of a different style (e.g. the Eames style), the grammar strategy would perhaps be different.

The TCG language addresses a design family, comprising a highly restricted solution space. The TCG was an existing specific SG that was incorporated in the MCG. Only a small number of rules was included, since the MCG addresses a lower level of shape detail than the TCG. This caused a loss in the style characterization, since Thonet chairs are defined by slight curves, a feature which is not addressed by the MCG. The incorporation of the TCG into the MCG was helpful to define the boundaries of both grammars and to test the MCG completeness.

The rule number is related to the level of similarity between the designs of the corpus. For instance, the TCG has a higher number of rules in the Back set, since it is the distinguishing feature of the style, and it does not have any rule in the Leg Base and Arms sets. New designs result from interpolations of the designs of the corpus; the less similar the designs of the corpus, the wider the variation that can be produced by new designs. This is observed in the new chairs generated by the TCG, which highly resemble the corpus chairs.

The ICG and the DJHG can be considered generic SGs. The grammars were developed from two different methods: the former from the analysis of a corpus of designs comprising different types and the latter from the union of two specific SGs. The ICG has significant a higher number of rules (58% against 34%) and contemplates much more types of designs; however, it does not ensure the prediction of all types (since the DJHG has rules that are not used by the ICG).

The common grammar DJCG is intended to merge two designers' styles; however, it contemplates a highly restricted solution space (it does not include Stretchers, Base and Arms). Instead, DJHG considers a wide solution space, where the style's features may be over blurred.

The grammars were developed across the four main versions. Version 0.1 considered DCG; version 0.2 considered DJHG (customizable to DCG and JCG); the version 1.1 considered ICG (customizable to TCG); and the version 1.2 considered MCG, customizable to DCG, JCG, TCG, ICG, DJHG, and DJCG. The higher the version, the higher the level of *genericness*, and the lower the level of shape detail. A grammar comprises different rule number across versions (e.g. DCG in versions 0.1, 0.2 and 1.2) because rules are reformulated, comprising an addition of rules (by rule decomposition) or a deletion of rules (by rule combination).

5.8 Conclusion

This chapter described the Multipurpose Chair Grammar (MCG), which corresponded to the fourth stage of the computational model. The MCG is a generic grammar, which can be restricted to more specific grammars (sub-grammars) and extended to more generic grammars (meta-grammars). The grammars described in this chapter address five levels of *genericness*, from the highest to the lowest: (1) Meta-Grammar, (2) generic MCG; (3) less generic grammars *Iconic Chair Grammar* (ICG) and *Daciano-Jasper Hybrid Grammar* (DJHG); (4) specific grammars Daciano Chair Grammar (DCG), *Jasper Chair Grammar* (JCG), and *Thonet Chair Grammar* (TCG); and (5) the *Daciano-Jasper Common Grammar* (DJCG).

Three tests were applied to the MCG: the descriptive test, the analytic test, and the synthetic test. These tests were applied in the evaluation of the capacity of the grammar in generating specific grammars and designs. The descriptive test was employed to generate grammars and designs from the corpus; the analytic test was employed to generate existing grammars and designs which do not belong to the corpus; and the synthetic test was employed to generate original grammars and designs.

The main contribution of this chapter relies on the MCG – a generic set grammar, intended to support the concept phase of multipurpose chair design. The MCG comprises 108 rules and 61 parameters. The descriptive, analytic and synthetic tests were innovatively applied to the evaluation of both grammars and designs. Moreover, methods for generating specific grammars from generic grammars, and for generating common and hybrid grammars were provided. The implementation of the MCG, described in the next chapter, was tested as a tool for designers.

The MCG can be further developed. The recommendations for future versions of the grammar are included in the next chapter (**The ChairDNA Design Tool**), within the recommendations for the implementation. Some of the main recommendations include the addition of rules and/or parameters to address a higher level of shape detail, to address connections between parts (beyond Leg extensions), and to detail the position of solid parts. Future work could also comprise (i) the application of the analytic test to other existing specific grammars, (ii) the application of the synthetic test to generate other new specific grammars, and (ii) the application of the Meta-Grammar to other grammars, considering languages of other product classes beyond multipurpose chairs.

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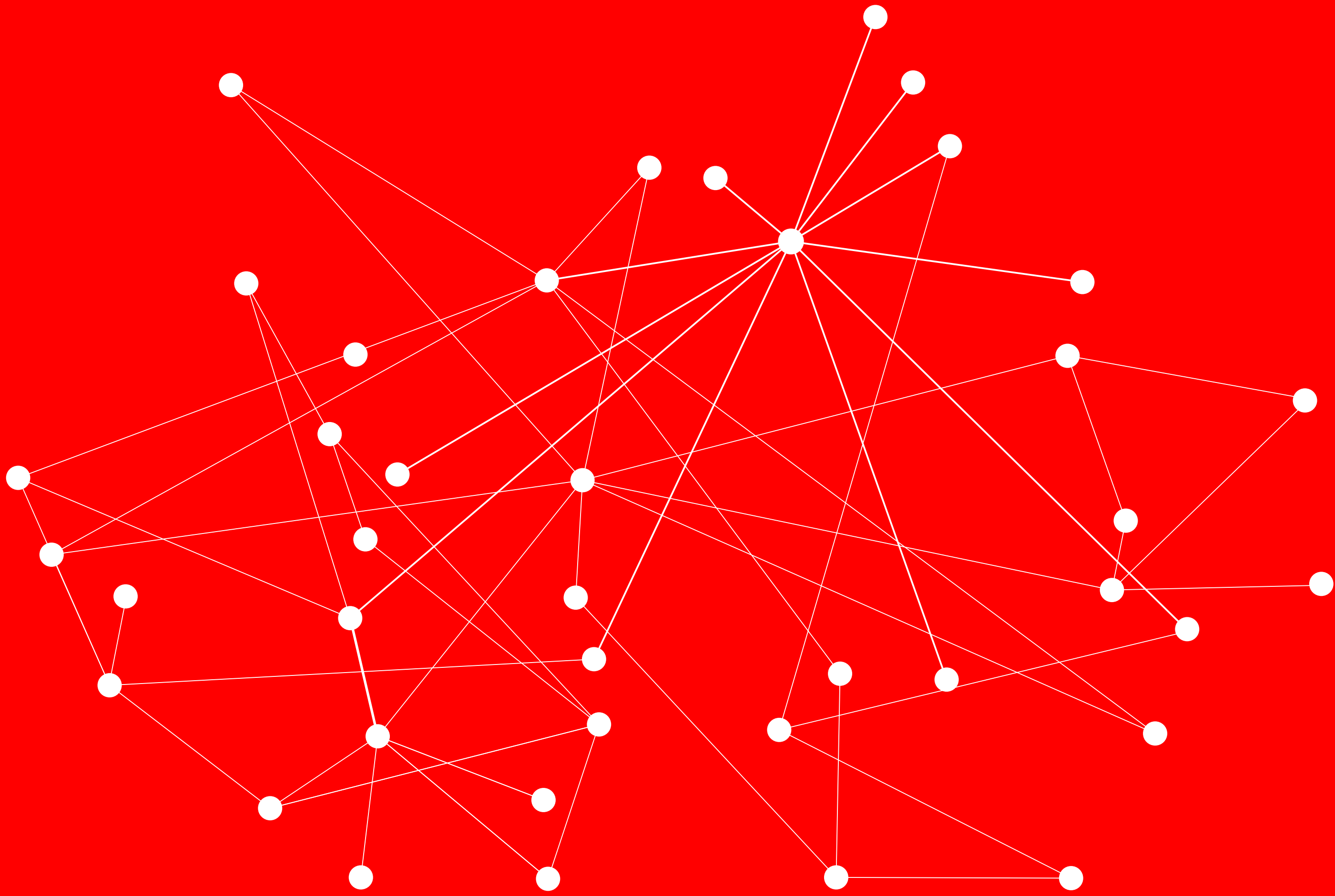
5.10 Appendixes



The ChairDNA Design Tool

6

6 THE CHAIRDNA DESIGN TOOL

The implementation of design tools in digital environments allows its refinement and enhancement of generation efficiency and speed. In this chapter, the implementation of the Multipurpose Chair Grammar into the digital design tool ChairDNA is described. The tool is oriented to provide a useful and intuitive interface for designers in the concept phase of the chair design process. The two major versions of ChairDNA (1.1 and 1.2) are discussed, as well as recommendations for future versions. The tool was developed according to a methodology for the implementation of set grammars into digital tools, through the translation of rules and parameters into user interface elements. A method for the implementation of specific grammars and a set of designs generated by the tool are presented. The tool was evaluated by the descriptive, analytic and synthetic tests.

6.1 Introduction

A shape grammar (SG) can be implemented in a digital environment using two different strategies: (i) it can be implemented in an SG interpreter or (ii) it can be translated into an SG specific implementation.

(i) An SG interpreter is a computer program that interprets an SG and produces results, allowing users to implement and use different SGs. Interpreters started to be developed from almost the origin of shape grammars (Gips 1975), and several examples have been elaborated ever since. The majority of interpreters are exemplified with implementations of simple abstract grammars, as the GEdit, which supports emergence (Tapia 1999), and the Shaper 2D (McGill & Knight 2004). Some few examples contemplate implementations of designs grammars, as the SGS interpreter (Chau et al. 2004), which implemented the Coca-cola bottle grammar, and the GRAPE interpreter (Grasl & Economou 2013), which implemented the Palladian grammar.

(ii) An SG specific implementation only supports one pre-defined grammar, and thus the user is only allowed to use that grammar. There are less research and applications on specific implementations; some sparse examples include the implementation of the Queen Anne grammar (Flemming 1987), the ice-ray grammar (Liew 2001), and the *Yingzao fashi* grammar (Li 2002).

Both options present strengths and weaknesses. SG interpreters have the ability to reproduce a large number of different grammars, unlike SG specific implementations, which only address one particular grammar and do not allow the user to change rules or parameters. However, SG interpreters are limited in the number of shape properties they can replicate (e.g., emergent shapes, 3D shapes, curvilinear shapes, and parametric shapes). Usually these systems focus on a particular aspect and disregard other features (McKay et al. 2012). Therefore, a complex design grammar is difficult to implement in an interpreter, since it requires a high amount of knowledge inherent to domain-specific design tasks (Li 2002). SG implementations, on the contrary, are focused on one design problem and therefore usually develop a higher number of shape properties. Finally, SG interpreters require the user to have some specific knowledge about SGs, while SG specific implementations do not necessarily require such knowledge.

There are two identified shortcomings within the research field of SGs implementations: (i) the lack of a clear implementation methodology and (ii) the lack of implementations of design grammars (Strobbe et al. 2016). This chapter intends to contribute to overcome these shortcomings, by (i) providing a methodology for implementing set grammars and (ii) by applying the methodology in the implementation of a design grammar. The methodology is focused on the development of a useful interface for designers, which is an identified shortcoming of currently available rule-based design tools (Chase 2005).

This chapter presents an implementation of the Multipurpose Chair Grammar (MCG), described in the previous chapter, into the digital tool ChairDNA. The development of the tool corresponds to the fifth stage of the computational model described in the **Introduction** chapter. ChairDNA is an interactive design tool, intended for the exploration of solutions in the concept phase of multipurpose chair design. The generation and edition of designs is made by adding and deleting chair components and manipulating shape parameters. The visualization of the outcomes is made in real-time in a 3D digital model, displayed in a variety of CAD applications (AutoCAD, Rhinoceros and SketchUp). ChairDNA is intended for product designers, both students and practitioners.

ChairDNA is a specific SG implementation, using a similar approach of the ice-ray SG implementation (Liew 2001). In both cases, rules are translated into checkboxes and parameters are translated into sliders and text-fields. However, in the former, intermediate states of the design can be visualized, while in the latter only the final design is displayed. The MCG was not implemented in an interpreter, because it required different shape properties and, moreover, it was intended for inexperienced users in SGs.

ChairDNA was programmed in Racket and uses Rosetta to ensure the connection with some CAD applications. ChairDNA comprises two major versions, whose launch date is related to two user evaluations (described in the chapter **User Evaluation of ChairDNA**):

1) *ChairDNA 1.1*: released in 2nd December 2014, for the First Evaluation. This version was developed in Racket v6.1.1 and Rosetta v1:53. The pilot test of the First Evaluation used a slight different version (*ChairDNA 1.1.0*, released in 21th November 2014);

2) *ChairDNA 1.2*: released in 15th January 2017, for the Second Evaluation. This version was developed in Racket v6.7 and Rosetta v2:01.

This chapter is structured as follows: firstly, the methodology for the implementation of set grammars is described. Secondly, ChairDNA 1.2 is detailed. Thirdly, an implementation methodology for specific SGs is presented and demonstrated. Finally, the generative capabilities of the tool are illustrated and tested.

6.2 Implementation Methodology

This section describes a methodology for implementing a set grammar into a digital environment (Garcia & Menezes Leitão 2018). The methodology comprises the translation of set grammar rules and parameters into graphical user interface (GUI) elements. This methodology aims to, on the one hand, control the combinatory explosion of rule application (typically inherent to SGs) and, on the other hand, provide a tool for inexperienced users in shape/set grammars, programming and 3D digital modelling. An implementation of a simple grammar is illustrated in **Fig. 6.1**, as an example. The methodology regards the following steps:

1) Rule sets (or rule stages) are translated into tabs, which are labelled with the name of the rule set; each tab contains the interface elements related to the rules and parameters of the corresponding rule set;

2) Rules are translated into checkboxes, which are labelled with the rule name;

3) Rule availability is translated into the checkbox status (enabled or disabled): if the rule is available (i.e., if the LHS of the rule matches the current shape), the checkbox is enabled; otherwise it is disabled (and the checkbox appears greyed out). This is illustrated in **Fig. 6.1** (bottom left) by the checkboxes R1 (enabled) and R2 (disabled);

4) Rule application is translated by the checkbox state (checked or unchecked): if the rule is applied (i.e., if the RHS is applied to the current shape), the checkbox is checked; otherwise it is unchecked. This is illustrated in **Fig. 6.1** by the checkboxes R1 and R2. R1 is the antecedent of R2: if R1 is unchecked, R2 is unchecked and disabled, otherwise R2 is enabled (and can be either checked or unchecked);

5) Rules which are applicable multiple times require an extra slider, which indicates the number of times the rule is applied (e.g. **Fig. 6.1**). If such rule contains parameters, there are two implementation options: (a) the same parameter value is used for all rule applications, or (b) different values are used for each rule application (and thus the number of sliders corresponds to the number of times the rule is applied);

6) Rules with different LHS and similar RHS (i.e., comprising the same labelled shape) are merged into a single checkbox. The choice of which rule to apply is made automatically with the match in the current shape;

7) Rules with more than one possible application (i.e., more than one match in the current shape) have to be revised in order to remove the ambiguity (i.e., to have only one possible match in the current shape);

8) Rule parameters are translated into sliders and text-fields, which are labelled with the parameter name. The slider value corresponds to the text-field value; the edition of the slider value changes the text-field value, and *vice versa*. The minimum, maximum and initial values of the slider correspond to the minimum, maximum, and default values of

the parametric range. Both sliders and text-fields are hidden if the corresponding checkbox is unchecked;

9) Rule parameter availability is translated by the slider status (enabled or disabled): if the parameter is usable by the respective rule, the slider in enabled; otherwise it is disabled. This is a consequence of the step 6 of the methodology, which states that several rules can be merged into a checkbox; this step is applicable when those rules do not use exactly the same parameters;

10) The current shape is translated into a digital model displayed in a CAD application, which is immediately updated whenever any GUI element is changed;

11) The initial shape is translated into the default shape in the CAD application, displayed when the implementation is opened.

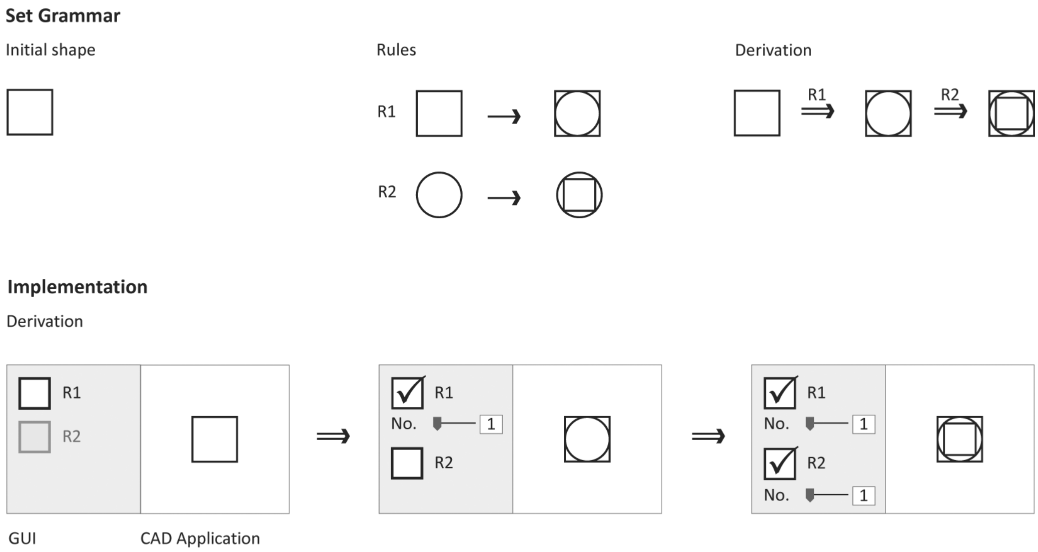


Fig. 6.1 Implementation of a simple set grammar

This methodology implies the encoding of the graphical representation of rules into a symbolic representation. The shapes of the LHS and the RHS are represented by labels. During the computation, each label comprises a logical value (true or false), which is used to assess the existence of those shapes in the current shape. A rule can only be applied if the shape of the LHS matches the current shape, i.e., if the corresponding logical value is true. This implementation method disables the user to edit the rules but is efficient to execute, supporting interactive changes on rules and parameters with immediate feedback in the generated 3D model.

6.3 ChairDNA 1.2

ChairDNA is a prototype of a tool for multipurpose chair design. The application allows the user to generate symmetrical chairs of many different types, while ensuring they obey correct anthropometric standards. Chairs may be generated by adding/deleting parts and editing shape parameters, until a desired solution is reached, or by editing predefined templates (loaded from a library or randomly generated).

The **Appendix 6.A.1** contains the ChairDNA 1.2 application for Rhinoceros and a template library with 26 iconic chairs. The tutorial is displayed in **Appendix 6.A.2**, the installation guide in **Appendix 6.A.3** and the quick start guide in **Appendix 6.A.4**. ChairDNA 1.2 requires the operating system Windows 64-bit and the CAD software Rhinoceros 5.

6.3.1 Requirements

The development of the ChairDNA tool comprised four functional requirements and four non-functional requirements:

1) *Functional requirements*: implement the MCG (described in the chapter **Multipurpose Chair Grammar**) according to the methodology aforementioned; implement two visualization modes (wireframe and solid); implement a command to export and import solutions from Excel spreadsheets; and implement the chairs of the **Multipurpose Chair Sample**.

2) *Non-functional requirements*: usefulness (provide a useful tool for designers), usability (provide a simple, intuitive and easy to learn interface), efficiency (provide quick feedback in response to user inputs), and portability (provide a tool which can be used with different CAD applications).

6.3.2 User Interface

The ChairDNA GUI can interact with one of the following three CAD applications: Rhinoceros, AutoCAD or SketchUp. **Fig. 6.2** shows a screenshot of ChairDNA with the generated **Antelope** chair (of the **Multipurpose Chair Sample**), displayed in the Rhinoceros CAD application. The **Appendix 6.B.1** displays screenshots of the remaining tabs of ChairDNA.

Within ChairDNA, the user can manipulate rules and parameters, by editing checkboxes and sliders. The interface includes four main types of elements: (1) *file menu* (contains commands related to file manipulation and the random generation mode), (2) *tabs* (contains display options and allows switching between groups of parts of the chair), (3) *checkboxes* (control the addition and deletion of chair parts), and (4) *sliders/text-fields* (control shape parameters). Within the CAD application, the user can visualize the current shape and edit visualization options.

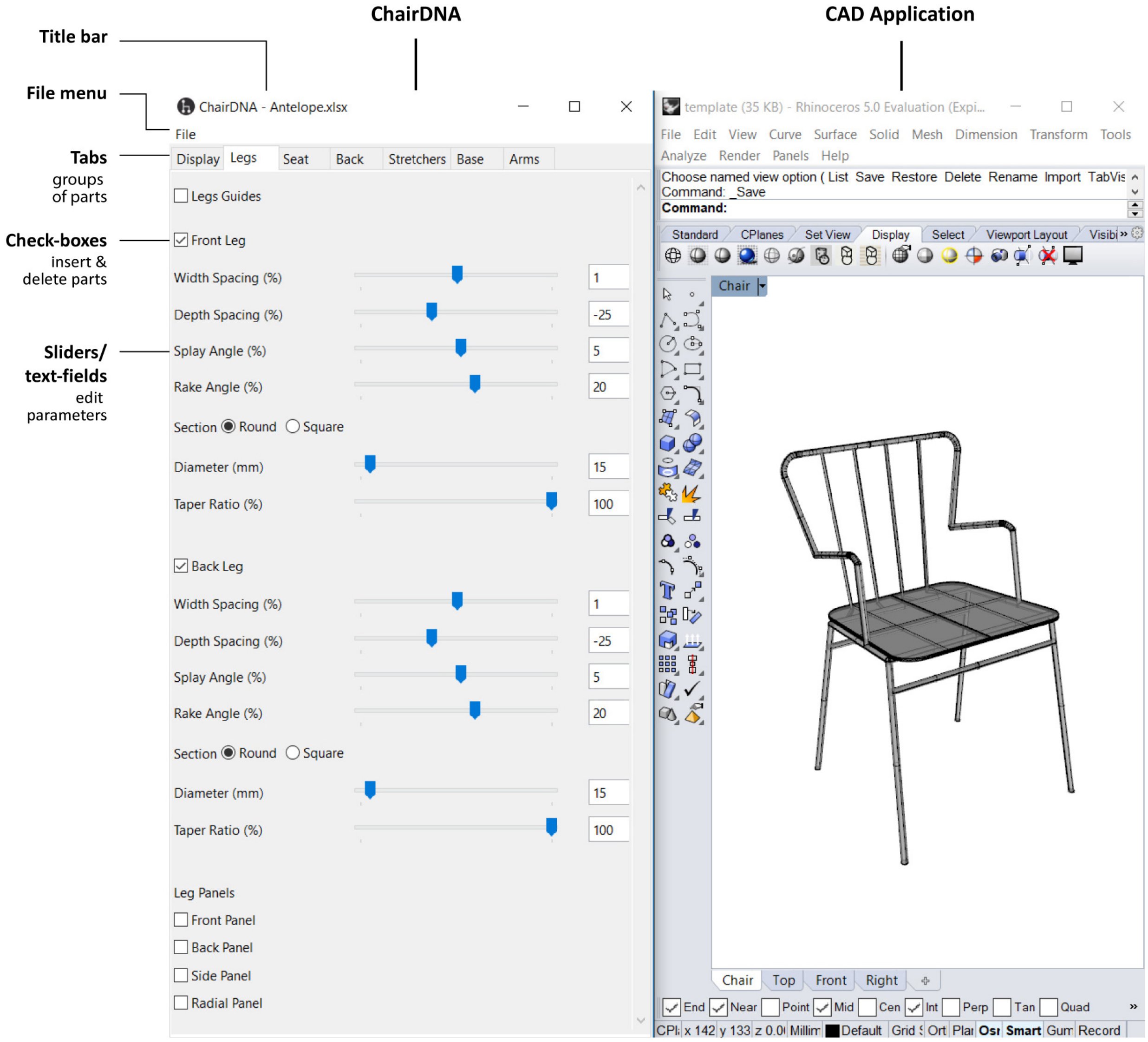


Fig. 6.2 Screenshot of ChairDNA 1.2 and Rhinoceros 5

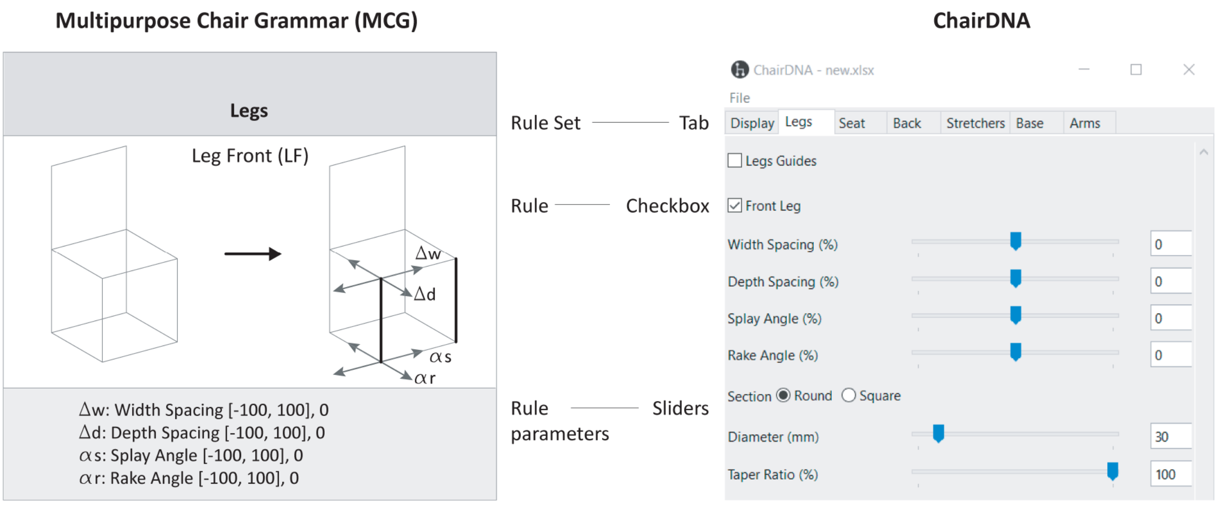
The name ChairDNA is an allusion to the genetic code, which codifies the similarities of a class and the differences of each individual. The application icon (at the left of the title bar) is an adaptation of the logo to a black background and a higher thickness (to be readable in a small size). The logo symbol is a stylized representation of a chair profile, and includes an allusion to the DNA molecule (representing atoms and their connections) and to knowledge-based diagrams (representing entities and their relations). The application icon and the logo are displayed in **Appendix 6.B.2**. The GUI layout appearance takes the settings of the operating system.[1]

[1] Default settings of Windows 10 (**Fig. 6.2**): application background colour: grey (RGB 240 240 240); title bar colour: white; font family: Segoe UI; font style: normal; font size: 9; font colour: black. Default settings in Windows 7 (**Fig. 6.8**): equal to Windows 10, except the title bar colour which is blue gradient (between RGB 153 180 209 and RBG 185 209 234).

6.3.3 Implementation of the MCG

ChairDNA is a set grammar implementation. The implementation of the MCG followed the method for implementing set grammars, previously described. The correspondence between the grammar MCG and the implementation ChairDNA is exemplified in **Fig. 6.3**. In the figure, the rule Leg Front is implemented in the checkbox Front Leg, which is enabled and checked. The four parameters of the rule (Width Spacing, Depth Spacing, Splay Angle and Rake Angle) were implemented into four sliders.

Fig. 6.3 Correspondence between the MCG and ChairDNA (adapted from Garcia & Menezes Leitão 2018)



The MCG was implemented into the ChairDNA application, according to the steps described in the methodology:

1) ChairDNA contains 7 tabs, each corresponding to a rule set. The Legs, Seat, Back, Stretchers, Base and Arms tabs address the groups of parts. The Display tab corresponds to the Solid Mode rule set. The Termination set of MCG was not implemented.

2) ChairDNA contains 46 checkboxes (which correlate to 39 chair parts and 7 guides) and 13 radio-boxes (which correlate to Solid Mode rules). All the 108 rules the MCG were implemented in ChairDNA (the termination rule was only implemented in the random mode). In both MCG and ChairDNA the user decides when to stop the generation process. However, in MCG once the termination rule is applied, it is ensured that the final design has the mandatory parts of a chair. This rule was not implemented in the manual generation mode of ChairDNA, in order to allow the generation of designs from sub-languages, as stools or tables (which can be obtained by not placing any backrest part). Meanwhile, ChairDNA includes a random generation mode that contemplates the termination rule, as it will be later described.

Solid Mode rules in MCG do not have a symbolic representation, since they can be applied to any part of the chair. For that reason, Mode-Solid Frame rules were implemented in ChairDNA for the Front Leg, Back Leg, Outer Frame and Inner Frame parts, and the Mode-Solid Panels rules were implemented for each group of parts. These rules are represented in ChairDNA as radio-boxes (comprising the choices round and square). This implementation would correspond to a rule where the LHS has a square section and the RHS a round section.

3) The rule availability was implemented according to the grammar rules. Checkboxes may be enabled or disabled: if the checkbox is enabled, the user can change its state; otherwise it cannot. By default (in the initial state), the available checkboxes are: Guides, Panels, Legs and Seat Outer Frame. The other checkboxes will become available as the parts are being added.

4) The rule application was implemented as described in the methodology. Checkboxes may be checked or unchecked: if the checkbox is checked, the part is inserted; otherwise the part is deleted. By default, only the checkboxes of the Guides, which correspond to the initial shape of the MCG (Guides, Legs Guides, Seat Guides, Back Guides, and Base Guides), are checked.

5) Only 4 rules implemented in ChairDNA can be applied multiple times (while in MCG all rules comprise that feature). Those rules correspond to the Seat and Back inner frame: Seat Cross Rail, Seat Long Rail, Back Cross Rail, and Back Splat. This special feature was implemented for demonstration purposes in these rules since their multiple application is frequently observed in chair design (e.g. in slat chairs). For those four rules, there is an extra slider called ‘Number’, which varies between 1 and 12 (the maximum value was adopted from the **DKR** chair). The implementation of the rule parameters followed the option (a) of the methodology, i.e., the same parameter value is used for all rule applications. However, this parameter has a different meaning when the Number is greater than 1. This is illustrated in **Fig. 6.4**, which displays the Seat Cross 1 rule (left) and its implementation (right). In MCG, the parameter *d* corresponds to the distance of the rail to the front edge of the Seat, and can be different for each application of the rule. In ChairDNA, when the number is greater than 1, the parameter *d’* corresponds to the distance between the rails, and is fixed for all the rule applications.

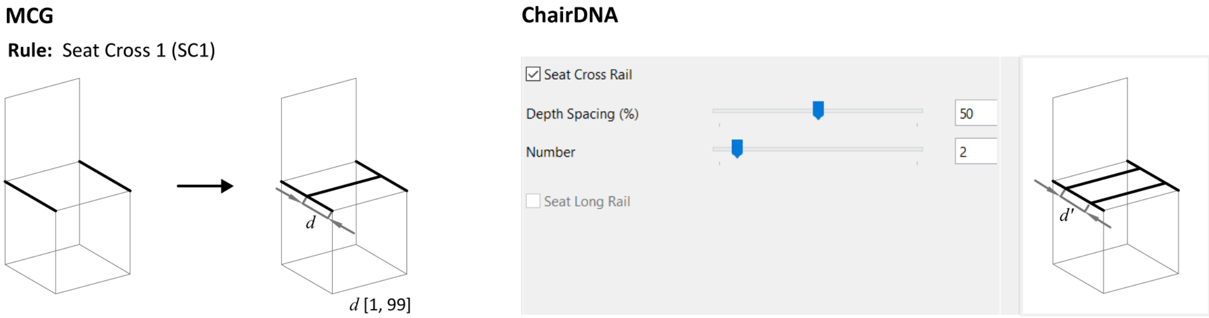


Fig. 6.4 Rule implementation, case 1: rules which are applicable multiple times (adapted from Garcia & Menezes Leitão 2018)

6) Rules with different LHS and similar RHS (i.e., that insert the same part of the chair) are merged into a single checkbox. This is exemplified in **Fig. 6.5**, which displays the implementation of the rules Seat Cross 1 (**Fig. 6.4**, left) and Seat Cross 2 (**Fig. 6.5**, left) into a single checkbox – Seat Cross Rail (**Fig. 6.5**, right). The Seat Cross 2 is applied only when the Seat Long rule matches the current shape, i.e., when the Seat Long Rail checkbox is checked, which is the case of the example.

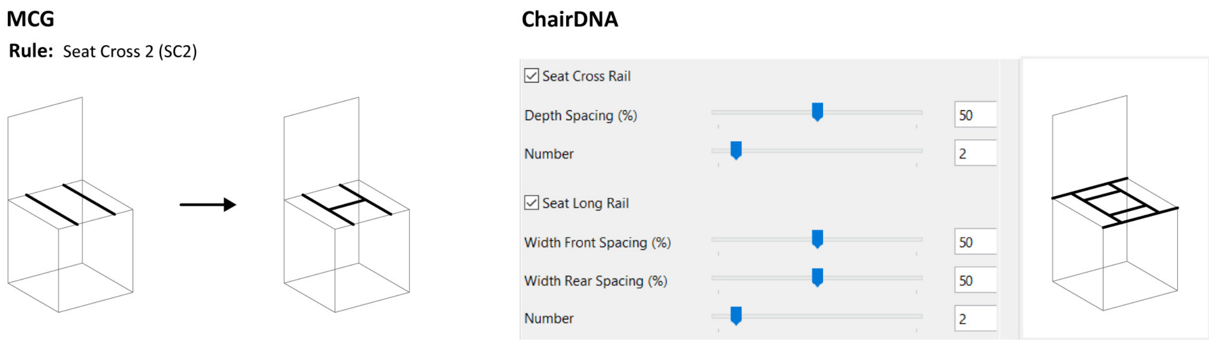


Fig. 6.5 Rule implementation, case 2: rules with different LHS and similar RHS (adapted from Garcia & Menezes Leitão 2018)

7) Rules with more than one possible application were revised in order to have only one possible application. This is exemplified in **Fig. 6.6** (left), where the rule Seat Cross 2 can have two different possible applications from the same current shape. ChairDNA always produces the second case (**Fig. 6.6**, right). The ambiguity was removed in order to avoid ChairDNA to generate a large number of options, which could cause two problems: lack of efficiency (from a computational perspective), and lack of usability (by forcing the user to choose an option among a large set).

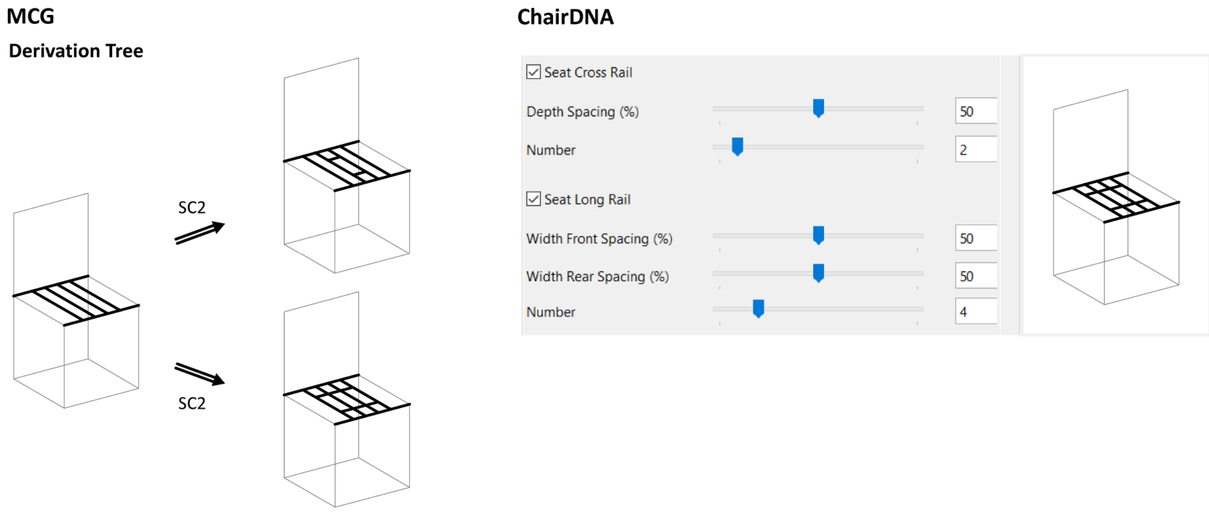


Fig. 6.6 Rule implementation, case 3: rules with more than one match in the current shape (adapted from Garcia & Menezes Leitão 2018)

8) ChairDNA contains 103 sliders and the equivalent text-fields, which correspond to the parameters of the chair parts. All the 61 rule parameters of the MCG were implemented in ChairDNA.

9) The rule parameter availability was implemented as described in the methodology. There are 5 rules whose parameters may not be always totally available: Seat Long, Back Splat, Leg-Stretchers Long, Leg-Base Long and Arm Support Side.

10) The current shape is displayed in one of three possible CAD applications. While using ChairDNA, the only available commands in the CAD application are visualization options (e.g. type of view, display modes, zoom and pan).

11) The initial shape was implemented as the default shape. Moreover, it was also implemented as a ChairDNA checkbox (the *Guides* checkbox in the Display tab). Therefore, in ChairDNA the initial shape can be hidden or revealed at any time during the derivation, while in MCG it is only removed at the end (with the termination rule).

The previous implementation steps described some differences between ChairDNA and MCG. Further comparisons can be made, regarding shape, rules, generation capabilities and display:

1) *Shape*: both ChairDNA and MCG use parametric 3D shapes. Both use points, lines (rectilinear and curvilinear), planes and solids as the basic shape elements. However, weighted shapes in ChairDNA only comprise different colours, while in MCG they address different colours and thicknesses.

2) *Rules*: ChairDNA uses both additive and subtractive rules, since the chair parts can be added or deleted at any time, while MCG currently only comprises additive rules. ChairDNA allows the user to open a given design (from a file) and edit its features. Therefore, with ChairDNA the user can both use an additive or a transformation design strategy, while with MCG the user is restricted to an additive strategy.

3) *Generation capabilities*: ChairDNA comprises a manual and an automatic generation modes, being the latter based on a random selection of rules and parameters. MCG currently only contemplates a manual generation of designs.

4) *Display*: rules are displayed in ChairDNA as checkboxes (and radio-boxes) and in MCG as graphical schemas; parameters are displayed in ChairDNA as sliders and text-fields, and in MCG as labels, ranges and numbers. The available rules at a certain derivation step are displayed in ChairDNA as enabled user interface elements, and thus are more easily detectable, since in MCG the user has to manually check the applicability of each rule. The initial shape and the current shape are displayed graphically on both systems. ChairDNA does not currently display the derivation diagram, unlike MCG.

Table 6.1 shows a comparison between MCG and ChairDNA, considering the number of rules and parameters *per* rule set. The correspondence between the ChairDNA interface elements and the MCG rules and parameters is displayed in **Appendix 6.B.3**.[2]

Table 6.1 Comparison between MCG and ChairDNA

Rule Sets		**Rule No.**		**Parameter No.**	
MCG	**ChairDNA**	**MCG**	**ChairDNA**	**MCG**	**ChairDNA**
Legs	**Legs**	9	9	8	17
Seat	**Seat**	19	10	11	20
Back	**Back**	18	10	11	20
Leg-Stretchers	**Stretchers**	18	10	9	16
Leg-Base	**Base**	22	10	8	15
Arms	**Arms**	18	8	8	15
Solid Mode	**Display**	3	2	6	0
Termination	**-**	1	0	0	0
	Total	**108**	**59**	**61**	**103**

6.3.4 Additional Commands

ChairDNA comprises other commands beyond the ones resulting from the implementation of MCG. The Display tab includes two commands which are related to visualization options:

1) *Guides*: turns on/off the guides of the Legs, Seat, Back and Base. These guides can be individually manipulated in the respective tabs. When the Guides checkbox is checked, all the guides that are turned off are turned on; otherwise, the guides that are turned on are turned off;

[2] ChairDNA has less 49 rules than MCG (step 2 added 10 rules, step 11 added 1 rule, step 2 removed 1 rule, and step 6 removed 59 rules). ChairDNA has more 42 parameters than MCG (step 2 added 38 parameters, and step 5 added 4 parameters).

2) *Mode*: changes the appearance of the model between Wireframe (default) and Solid.

The file menu comprises the following commands:

1) *New*: resets ChairDNA to the initial state;

2) *Open*: imports a design from an Excel file. The design can be opened from a predefined template library (ChairDNA displays a library with 26 iconic chairs) or from a file previously saved by the user. The Excel file contains a list of values related to the chair, and is editable (i.e., the values can be changed directly in the Excel spreadsheet). When the user opens a file in ChairDNA, the state of the interface elements changes in order to match the values in the Excel file, and the 3D model displayed in the CAD application is updated. All the values in the Excel file are converted to integer numbers in ChairDNA. The user can then proceed in the generation process by manipulating the interface elements;

3) *Save/Save as*: exports a design to an existing or new Excel file. The file stores the values of the current state of the design;

4) *Random*: generates a random design. The random mode is processed as follows: starting from an initial value (called *seed*); the random generator produces a series of apparently random values. In the case of ChairDNA, random values can be numbers (within a range) or logical values. Every time the command random is invoked ChairDNA produces a different random solution. However, every time the program is executed it produces the same sequence of solutions, for the same seed[3]. The random mode can be useful for the developer (for debugging) and for the users (by suggesting new directions or ideas). This generation mode is applying the termination rule of the MCG, thus it only generates designs that comprise the basic requirements of a chair. The random mode is also rejecting solutions which do not respect the antecedents (i.e., comprising checked checkboxes with its antecedents unchecked), since the random values do not take into account the generation sequence;

5) *Exit*: quits ChairDNA.

ChairDNA provides error feedback to the user. Two kinds of errors can occur: the ones that allow the user to proceed (usually by undoing the previous action) and the ones that cause the system crash. When the first case occurs, the label ERROR appears in the title bar, next to the application name. This kind of feedback has the advantage to be less intrusive than a dialog box, but it becomes less perceptible.

[3] The current seed is 4321. It can only be edited in the source code (is not available to the user).

6.3.5 Programming Strategy

ChairDNA is encoded in the Racket programming language (Felleisen et al. 2013). The language handles abstract syntax, supports multiple programming paradigms, is general purpose and is open-source. Racket is a dialect of the Scheme programming language which, in turn, is a dialect of Lisp. The programming environment used was DrRacket IDE, a pedagogic programming tool formerly developed for Scheme (Findler et al. 2002), but currently applicable to several languages. ChairDNA can be connected with one of the following three CAD applications: AutoCAD, Rhinoceros and SketchUp. The connection to the CAD application is established by Rosetta (Lopes & Leitão 2011).

The source code is divided into two files, one concerning the geometry of the chair and other comprising the GUI elements. The geometry file contains five images, directly embedded in the program (a feature supported by DrRacket). The images illustrate parts of the code, according to the approach of illustrated programming (Leitão, Lopes & Santos 2014). The schemas contain the identification of points, lines and dimensions used in the code. One example is given in **Fig. 6.7**, illustrating the Outer Frame function.

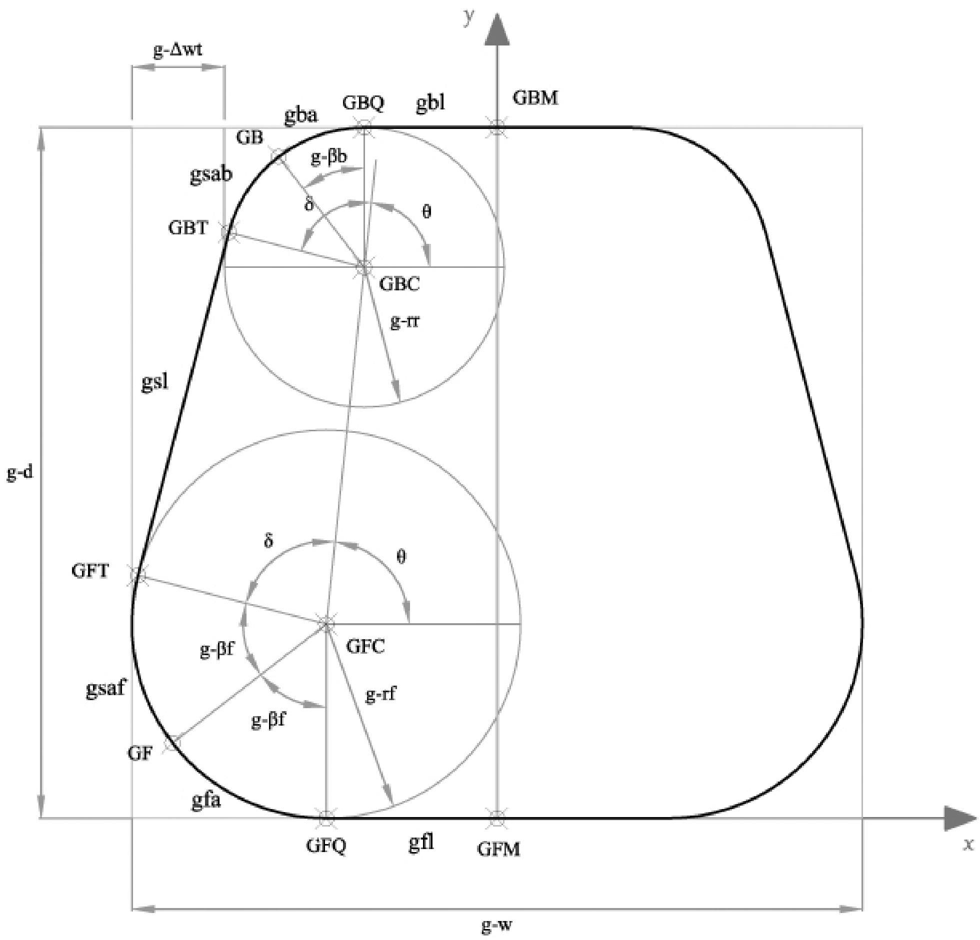


Fig. 6.7 Illustration of the Outer Frame function

The ChairDNA code contains three main kinds of functions: (1) geometric generic functions; (2) geometric chair functions, and (3) GUI functions, as described below.

(1) *Geometric generic functions*: Rosetta already contains a library with a large number of geometric functions. However, ChairDNA required the development of other generic geometric functions (as the example displayed in **Appendix 6.C.1**). Consequently, the development of ChairDNA contributed to improve some Rosetta functions.

(2) *Geometric chair functions*: the implementation of the MCG followed a generic programming paradigm, in which generic functions are instantiated in several specific functions. In the light of this programming style, the implementation of the MCG comprised the implementation of some rules of the Meta-Grammar, described in the chapter **Multipurpose Chair Grammar**, which are based on the Meta-Ontology, described in the chapter **Multipurpose Chair Ontology**. Because the MCG comprises many similar rules, this programming strategy ensured coherence and avoided duplication. The implemented generic functions and the corresponding specific functions are:

1) *Leg*: corresponds to the meta-rule of Leg. This function is applicable to the Front and Back Legs specific functions.

2) *Leg Panel*: includes the meta-rules of Leg Panel 1 and Leg Panel 2. This function is applicable to the Leg Panels (Front, Back, Side and Radial) specific functions.

3) *Outer frame*: defines the parametric shape of the outer frame (described in the Meta-Ontology), and contains the following meta-rules: Guides, Front Rail 1, Back Rail 1, Side Rail 1, and Panel. This function is applicable to the specific functions addressing the following groups of parts: Seat, Back, Stretchers, Base, and Arms. Note that the Arms specific function only uses half of the shape.

4) *Cross-Long Rail*: contains the Cross Rail meta-rules (1-2) and the Long Rail meta-rules (1-6). This function is applicable to the specific functions addressing the following groups of parts: Seat, Back, Stretchers, and Base.

5) *Radial Rail*: includes the Radial Rails meta-rules (1-3). This function is applicable to the specific functions related to the following groups of parts: Seat, Back, Stretchers, and Base.

Appendix 6.C.2 displays the *Leg*, *Outer Frame*, and *Radial Rail* generic functions and the corresponding specific functions. These functions have associated illustrations.

The implementation methodology requires a symbolic translation of rules, being the shapes of the LHS and the RHS represented by labels. ChairDNA uses an internal symbolic notation of the rules; for e.g., the Back Upright 1 rule is represented as follows: lb → lb + bu. The labels have an associated logical value, which dictates their existence in the current shape.

(3) *GUI functions*: these functions include tabs, checkboxes, radio-boxes, sliders and text-fields. **Appendix 6.C.3** displays the GUI functions concerning the Seat tab.

6.3.6 New Features Developed from ChairDNA 1.1

ChairDNA 1.1 corresponds to the implementation of the version 1.1 of the MCG, which addresses the Iconic Chair Grammar (ICG). A screenshot of ChairDNA 1.1 is displayed in **Fig. 6.8**.

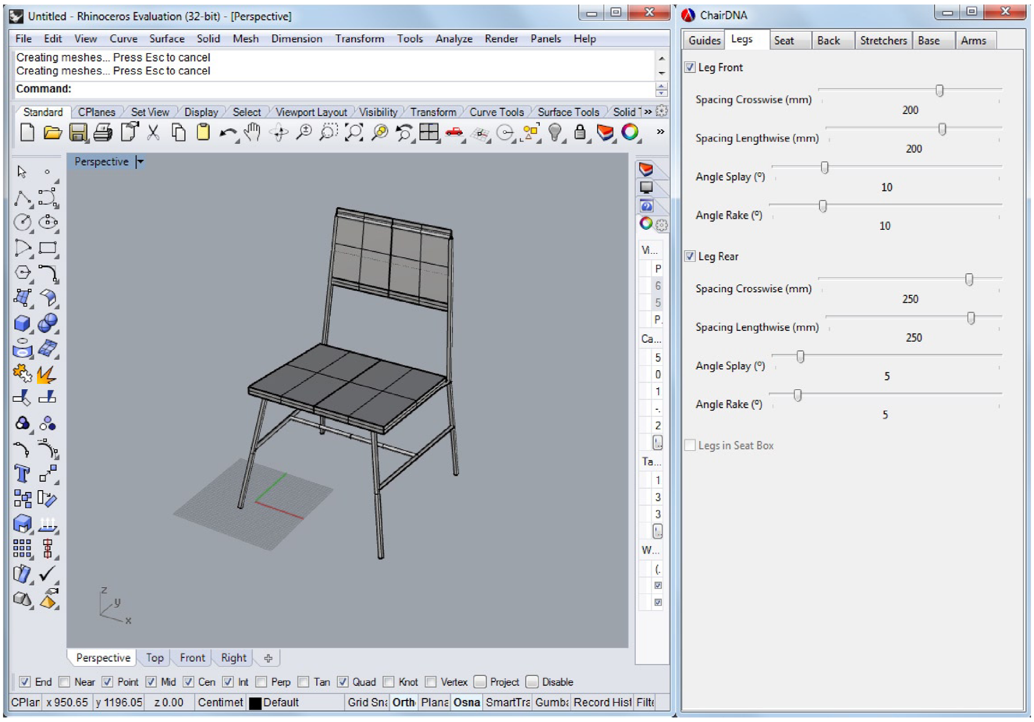


Fig. 6.8 Screenshot of ChairDNA 1.1

ChairDNA 1.1 was developed from a very similar version (ChairDNA 1.1.0), launched a few days earlier, for the pilot test of the First Evaluation. The new features of ChairDNA 1.1 (in relation to ChairDNA 1.1.0) are available in **Appendix 6.D.1**.

ChairDNA 1.1 comprised 7 tabs, 38 checkboxes, 4 radio-boxes, and 41 sliders. ChairDNA 1.2 contains 7 tabs, 46 checkboxes, 13 radio-boxes, and 103 sliders. Overall, the latter version comprehends an increment in the number of interface elements of almost 200% in relation to the former version. ChairDNA 1.2 comprised the edition, deletion and addition of elements, in relation to the former version; these changes are quantified in **Table 6.2**. The new features of ChairDNA 1.2 (in relation to ChairDNA 1.1) are detailed in **Appendix 6.D.2** and are summarized below. The features increment resulted from three main processes:

Specification: features were specified to more particular groups of parts:

1) *Solid Mode*: applicable to Front and Back Leg, Inner and Outer frames (11 radio-boxes and 38 sliders); in ChairDNA 1.1, Solid Mode elements were applicable to the entire chair;

Inheritance: features of some parts were inferred to other parts:

2) *Guides*: Legs, Seat, Back, Stretchers, and Base Guides (5 checkboxes); Back radii, Width and Taper Width; Stretchers Tilt Angle and radii; Base Width, Depth and radii; and Arms Tilt Angle and radii (14 sliders);

3) *Panels*: 4 Leg Panels and Stretchers, Base and Arm Panels (7 checkboxes);

4) *Long rails*: Long Stretcher and Base Long Rail (2 checkboxes); Long Stretcher Width Front and Rear Spacing; Base Long Width Front and Rear Spacing; Back Splat Width Bottom Spacing; and Arms Side Support Depth Bottom Spacing (6 sliders);

5) *Back rails*: Back Bottom Rail and Back Radial Rail (2 checkboxes), and Back Upright Height (1 slider);

Scratch: new features were introduced from scratch:

6) *Taper Ratio:* Front and Back Leg Taper Ratio (2 sliders);

7) *Number*: Seat Cross, Long and Radial Rails Number; Back Cross Rail and Splat Number; and Base Radial Rail Number (6 sliders).

Table 6.2 Quantitative changes in ChairDNA 1.2 in relation to ChairDNA 1.1

	ChairDNA 1.1	**ChairDNA 1.2**	**Added**	**Edited**	**Deleted**	**Unchanged**
Tabs	7	7	0	1	0	6
Checkbox	38	46	16	26	8	4
Radio-box	4	13	11	1	2	1
Slider	41	103	67	30	5	6
TOTAL	**90**	**169**	**94**	**58**	**15**	**17**

6.3.7 Recommendations

The list of recommendations for future versions of ChairDNA can be consulted in **Appendix 6.D.3**. There are 74 recommendations, comprising 21 bugs, 16 editions of features, and 37 additions of features. For each recommendation, it is mentioned its source (First Evaluation, Second Evaluation or developer) and the priority level (low, medium or high). The recommendations list relates to the plan stage of the computational model, version 2.1 (**Introduction** chapter).

6.4 Specific Grammars

This section provides a method for implementing specific grammars. This method is based on the method for *generating a specific SG from a generic SG* (demonstrated in the chapter **Multipurpose Chair Grammar**), which defines a specific SG by three types of rules and three types of parameters. For each type, the implementation method indicates a change in the state of the corresponding interface element (checkboxes and sliders):

1) *Enabled checkbox*: corresponds to the *optional rule;* is an available checkbox that can be either checked or unchecked;

2) *Disabled-checked checkbox*: corresponds to the *mandatory rule*; is an unavailable checkbox, which is always checked;

3) *Disabled-unchecked checkbox*: corresponds to the *deleted rule;* is an unavailable checkbox, which is always unchecked;

4) *Enabled slider*: corresponds to the *optional parameter;* is an available slider that can contemplate a restricted or an unrestricted range;

5) *Disabled slider*: corresponds to the *mandatory parameter*; is an unavailable slider whose value is different from the default value;

6) *Disabled-default slider*: corresponds to the *deleted parameter*; is an unavailable slider whose value is equal to the default value.

The methodology was applied to calculate the implementation values of the seven sub-grammars mentioned in the chapter **Multipurpose Chair Grammar**: Daciano Chair Grammar (DCG), Jasper Chair Grammar (JCG), Thonet Chair Grammar (TCG), Iconic Chair Grammar (ICG), Daciano-Jasper Common Grammar (DJCG), Daciano-Jasper Hybrid Grammar (DJHG), and Synthetic Chair Grammar (SCG). The Mode and Guides checkboxes comprise exceptional cases, since they are always enabled. **Appendix 6.E.1** displays an Excel spreadsheet with the implementation values.

Although the method and the implementation values of specific SGs are provided, these grammars were not actually implemented in ChairDNA. However, the mock-up of the envisioned interface is displayed in **Fig. 6.9**. The example shows the Back tab of ChairDNA, with the implemented Thonet grammar, and the chair **214** being generated. Different types of interface elements are observable:

1) *Enabled checkboxes*: Back Guides, Back Bottom Rail, Back Cross Rail, Back Splat and Back Panel;

2) *Disabled-checked checkboxes*: Back Upright and Back Top Rail;

3) *Disabled-unchecked checkboxes*: Back Radial Rail; including disabled-unchecked radio-boxes (Outer and Inner Frame Sections);

4) *Enabled sliders*: Back Cross Rail Height, restricted to [75, 99];

5) *Disabled sliders*: Outer and Inner Frame Section Diameters;

6) *Disabled-default sliders*: Back Upright Height and Back Cross Rail Number.

The envisioned usage of a specific grammar would be as follows: by opening an Excel file (comprising the values of a grammar), the checkboxes and sliders would change their states according to the methodology previously described. Some elements would become restricted and a Style Mode would be selected. Within that mode, the user would be able to manipulate the available options. All the features would become unblocked by deselecting the Style Mode.

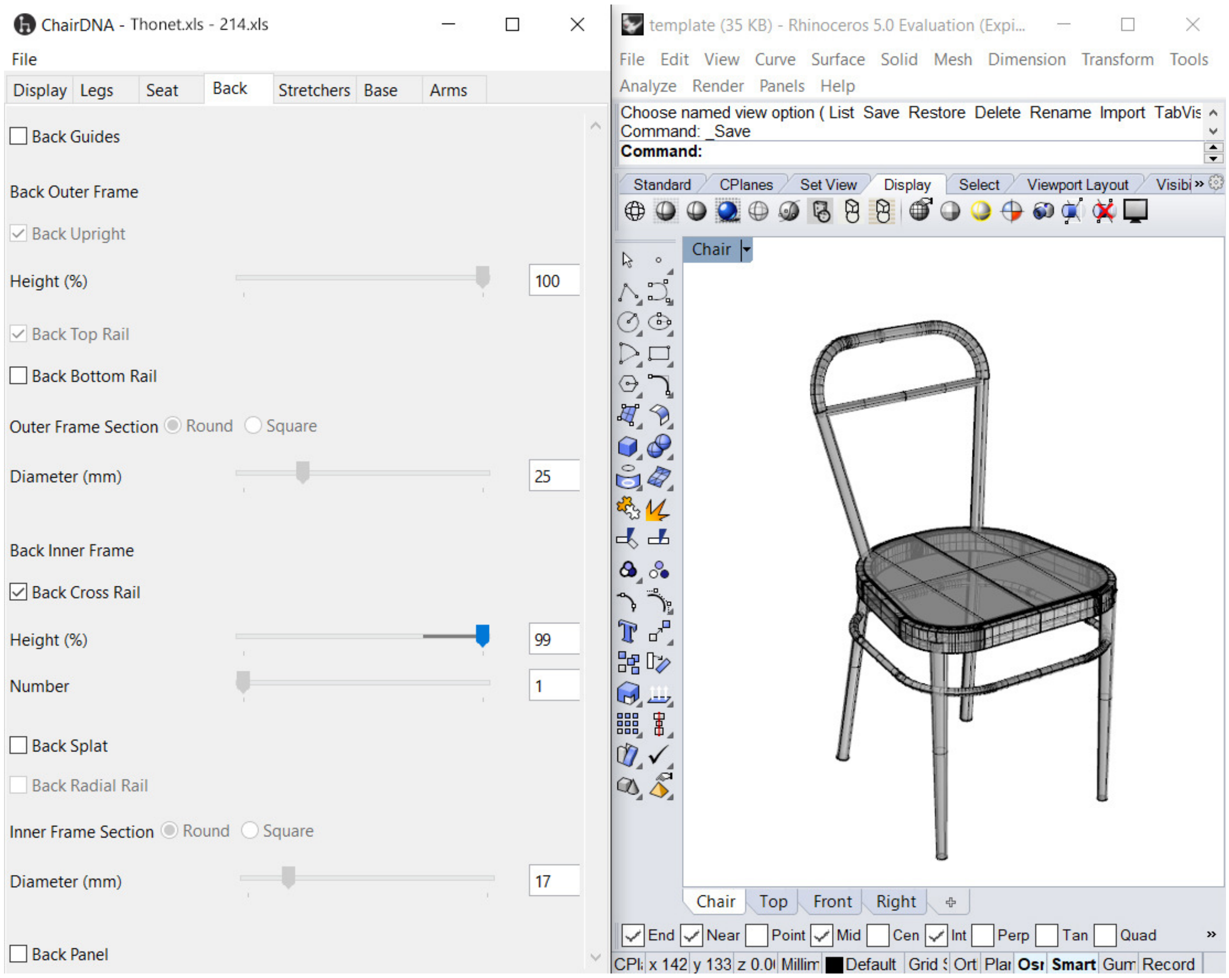


Fig. 6.9 Mock-up for the implementation of the Thonet grammar

6.5 Designs

This section illustrates several designs generated in ChairDNA. The designs are divided by design styles, design types, and design collections (generated by the developer using ChairDNA), and random designs (automatically generated by ChairDNA). The implementation of designs comprehends the introduction of values, either in ChairDNA or in an Excel spreadsheet readable by ChairDNA. The majority of the designs presented in this chapter only consider an accurate precision in the overall measures of the chair (width, depth, height and seat height); the remaining values were approximately attributed, based on the 3D models available in the producer's website.[4] Only Thonet designs regarded a precision in all values. The values of all the designs presented in this section are available in **Appendix 6.E.2**.

[4] Some models available in the producer's website are inaccurate (e.g. in the **DCW** model, the back leg is not angled).

6.5.1 Design Styles

This section comprehends designs from two individual design styles (Daciano and Jasper), common and hybrid designs between those two styles, and one design family manufactured by one company (Thonet). Each style is defined by the specific grammars previously described (respectively, DCG, JCG, DJCG, DJHG and TCG). The designs include corpus designs and existing designs (documented in the chapter **Multipurpose Chair Sample**) and new designs, generated in ChairDNA and restricted to the mentioned grammars.

Daciano Designs

Daciano designs relate to the individual style of the Portuguese designer Daciano da Costa. **Fig. 6.10** illustrates eight designs generated in ChairDNA within the DCG restrictions. It includes the five designs from the corpus, one existing design and two new designs. From the analysis of the DCG and the corpus designs, qualitative characteristics of the style may be inferred. The chairs are three- and four-legged without angles or taper. The seat is either square or semi-circular and the backrest can be solid or open. The chairs do not have stretchers and the base is rarely used. The arms supports are extended from both front and back legs and the chair frame only comprises square sections.

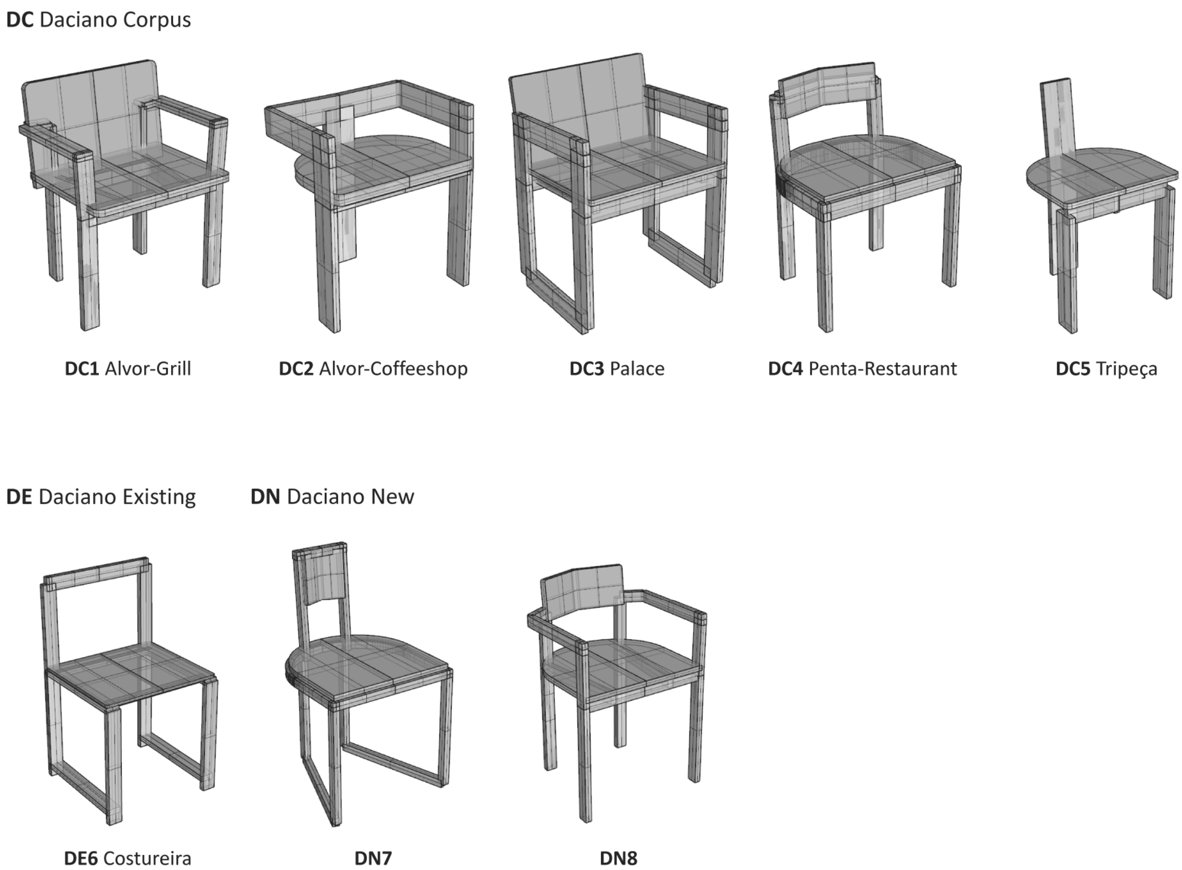


Fig. 6.10 Daciano designs generated in ChairDNA

Jasper Designs

Jasper designs address the individual style of the English designer Jasper Morrison. **Fig. 6.11** depicts eight designs generated in ChairDNA within the JCG restrictions. It includes the five designs from the corpus, one existing design and two new designs. Several generic characteristics of the style can be inferred from the analysis of the JCG and the corpus designs. The designs comprise four-legged chairs with slight angles and taper. The seat usually has a trapezoid shape, which can be square or rounded, and the back is either solid or open. The stretchers are rarely used, and the chairs do not have base. The sparse examples of arms comprise a cross arm rail format. Lastly, the frame section can be round or square.

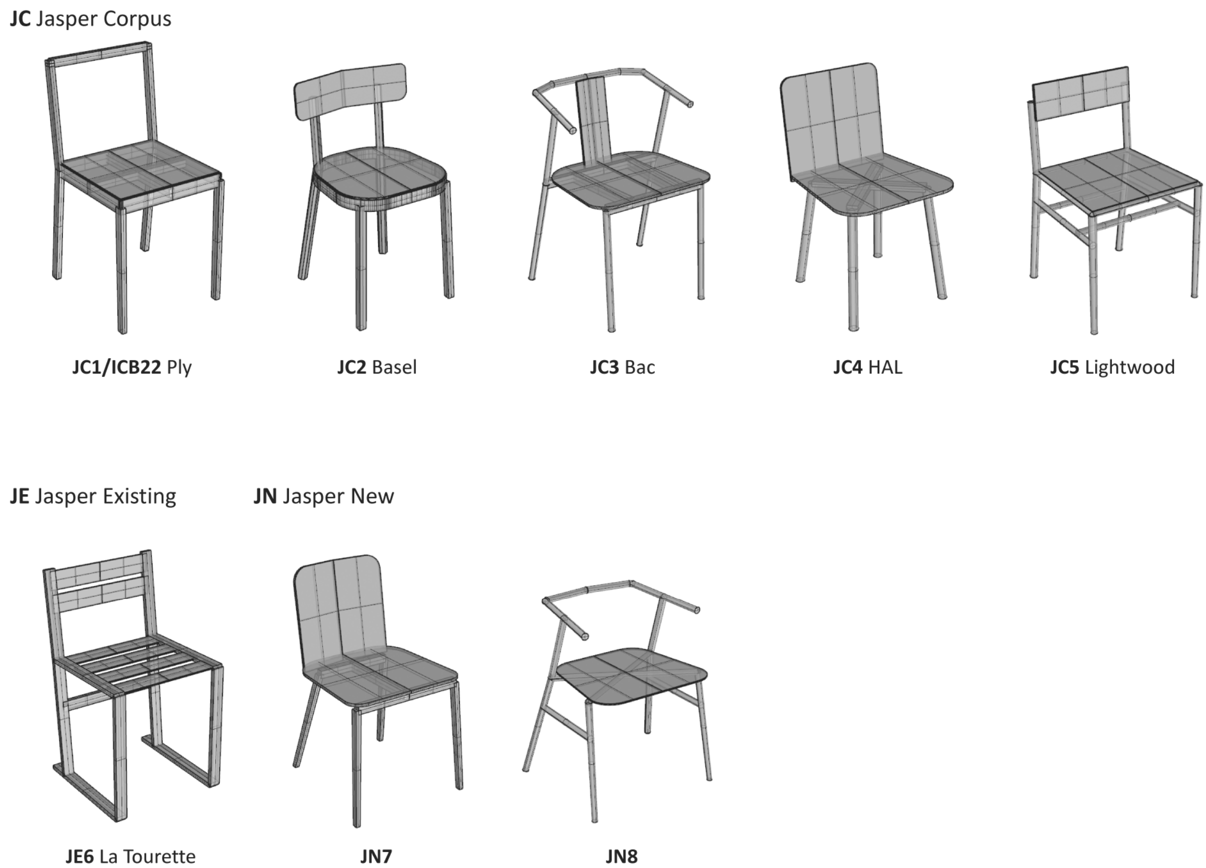


Fig. 6.11 Jasper designs generated in ChairDNA

Daciano-Jasper Common and Hybrid Designs

This section presents new common and hybrid designs between the two aforementioned individual styles (Daciano and Jasper). **Fig. 6.12** illustrates two common designs and two hybrid designs generated in ChairDNA, respectively within the DJCG and the DJHG restrictions. The common designs are highly restricted, since they only comprise straight four-legged chairs. The seat is never tapered and the back can be solid or open. The chairs do not contemplate stretchers, base and arms. Lastly, the frame always comprises a square section.

On the contrary, hybrid designs contemplate a much wider solution space, although more restricted than the MCG. This is visible in the design **DJH1**, which is the possible representation of the chair **214** following the DJHG restrictions. In relation to the chair **214** generated without restrictions (**Fig. 6.15**, design **ICA1/TC1**), it comprises two missing parts (Back Cross and Front Stretcher), three missing parameters (Back Taper Width and Stretchers Radii), and four more restricted parametric ranges (Front Leg Taper Ratio, Back-Seat Angle, Back Top Radius, and Stretchers Outer Frame Diameter).

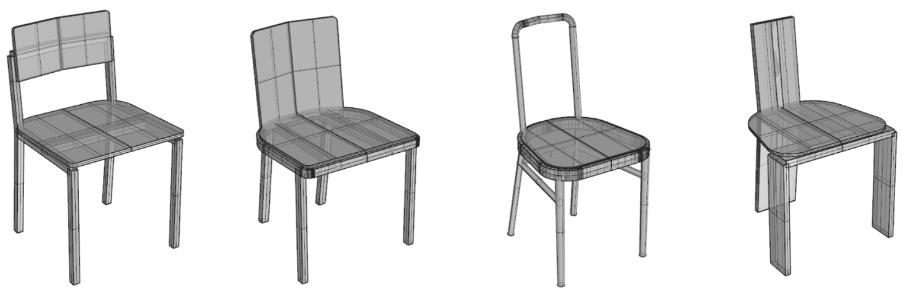


Fig. 6.12 Common and hybrid designs generated in ChairDNA

Thonet Designs

Thonet designs address a family of designs manufactured by the German company Thonet GmbH. **Fig. 6.13** shows five designs generated in ChairDNA within the TCG restrictions, including two designs from the corpus (the chair **214**, also from the corpus, is displayed later in **Fig. 6.15**), one existing design, and two new designs. The Thonet style is here restricted to a design family, since the designs only comprise variations in the backrest inner frame.

Fig. 6.13 Thonet designs generated in ChairDNA

The implementation of the designs from the corpus (chairs **214**, **215** and **218**) was made according to an accurate extraction of values from a 3D model. The extraction process comprehended three steps: (1) extraction of the geometric information readable by ChairDNA (i.e., wireframe skeleton and sections outline), (2) conversion of the geometry to the abstraction level of ChairDNA (i.e., translation of curves to lines and arcs), and (3) conversion of the geometric information to numeric information, which is stored in an Excel spreadsheet or inserted in ChairDNA. **Fig. 6.14** shows, on the left, the 3D digital model of the chair **214** established by Barros (2015), which was used to develop the model generated in ChairDNA (on the right), comprising a higher abstraction level. The figure displays both wireframe and solid models.

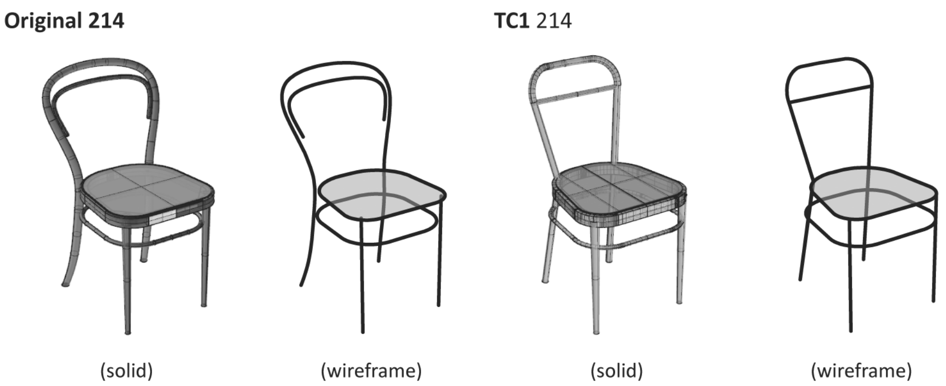


Fig. 6.14 Chair 214: original (left) and generated in ChairDNA (right)

6.5.2 Design Types

This section presents several designs addressing different design types. It comprehends corpus designs and existing designs (documented in the chapter **Multipurpose Chair Sample**) generated in ChairDNA using the ICG restrictions, and new designs generated in ChairDNA without any specific grammar restriction.

Iconic Designs

Iconic designs address Modern Iconic chairs from different types. This section presents several designs generated in ChairDNA within the ICG restrictions; **Fig. 6.15** shows 25 designs from the corpus and **Fig. 6.16** illustrates 7 existing designs (including six chairs and one stool). The **Ply** chair, which is also part of the corpus, was previously displayed in **Fig. 6.11**.

The designs cover a wide variety of design types, including one- to four-legged chairs, chairs with square, circular, semicircular or trapezoid seats, chairs with different backrest configurations (e.g. solid, open, ladder back or splat back), chairs with different stretchers and base shapes (e.g. X, H and U shapes), and arm and armless chairs.

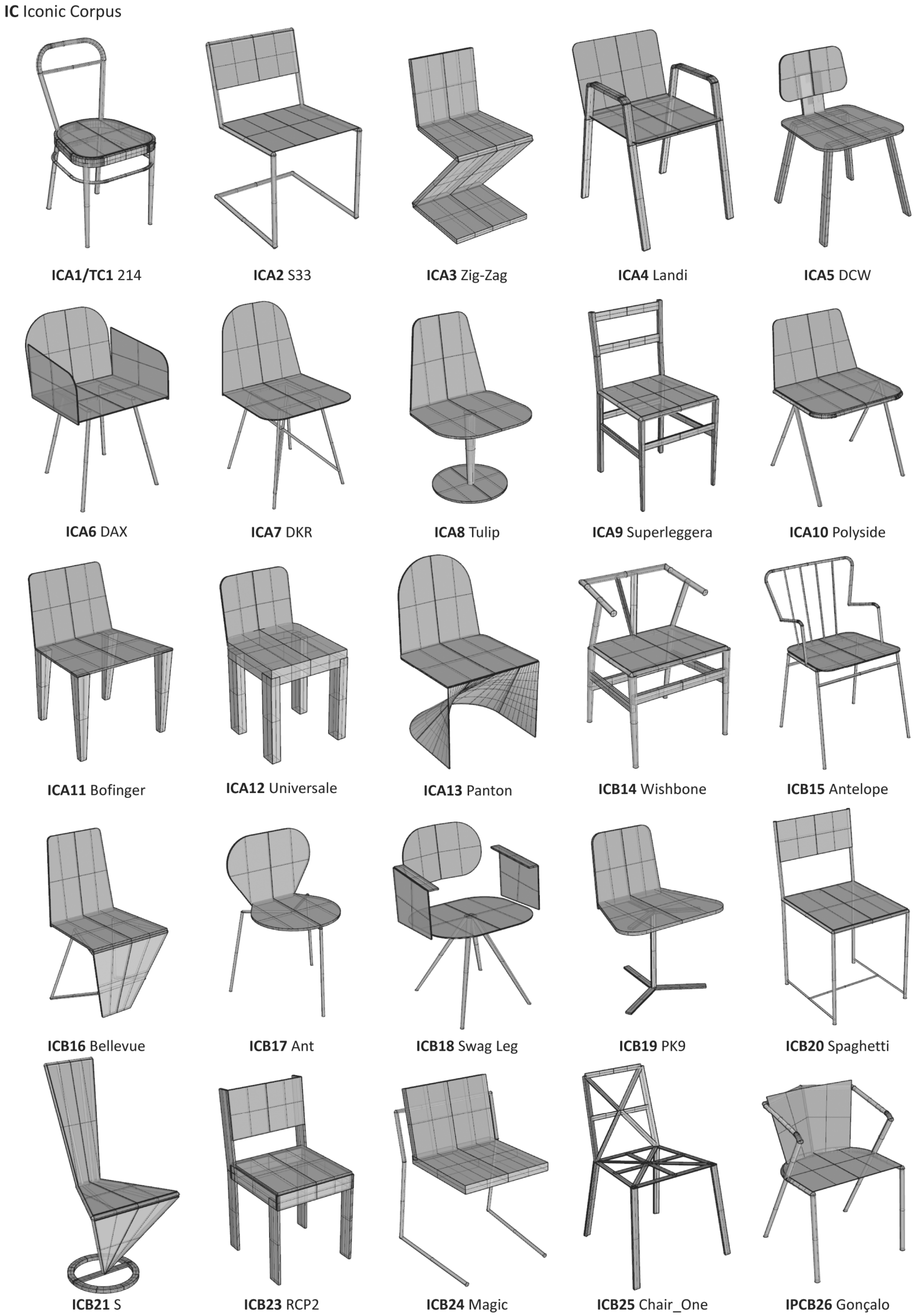


Fig. 6.15 Iconic designs (corpus) generated in ChairDNA

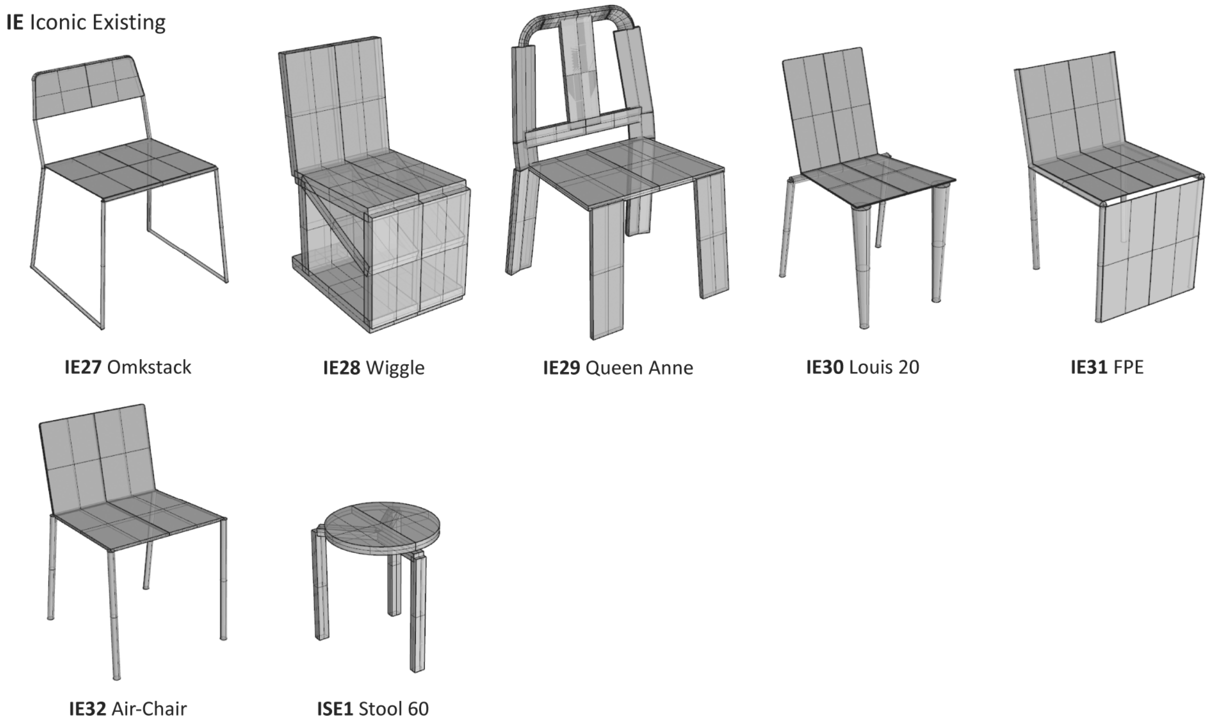


Fig. 6.16 Iconic designs (existing) generated in ChairDNA

New Design Types

The designs of this section address types described in the **Multipurpose Chair Ontology** that are not represented in the chairs of the **Multipurpose Chair Sample**. **Fig. 6.17** illustrates 20 new designs generated in ChairDNA. The labels of the designs are related to the IDs attributed in the ontology of types. Every group of parts (except the Back group) comprises new generated types, as described below:

1) *Legs*: 1-legged cantilever chairs (L1F and L1B), 2-legged pedestal chairs (L2FB and L2S), X-legged chairs (L4X1, L4XII, L4X=, and L4XC), chairs with solid panelled legs (L4●II, L4●=, L4●X, L4●U, L4●UR and L4●O), and angled-legged chairs (L4IS, L4ISR, L4OS, and L4IR);

2) *Seat*: chairs with a 5 star-shaped seat (S*5);

3) *Stretchers*: chairs with H-shaped stretchers (LSHR), U-shaped stretchers (LSUR) and semicircular stretchers (LSΦ);

4) *Base*: chairs with U-shaped base (LBU), single rail base (LB1), trapezoid base (LBΔ), parallel base (LB=), H-shaped base (LBH and LBHR) and 5 star-shaped base (LB*5);

5) *Arms*: chairs with circular arms (AO).

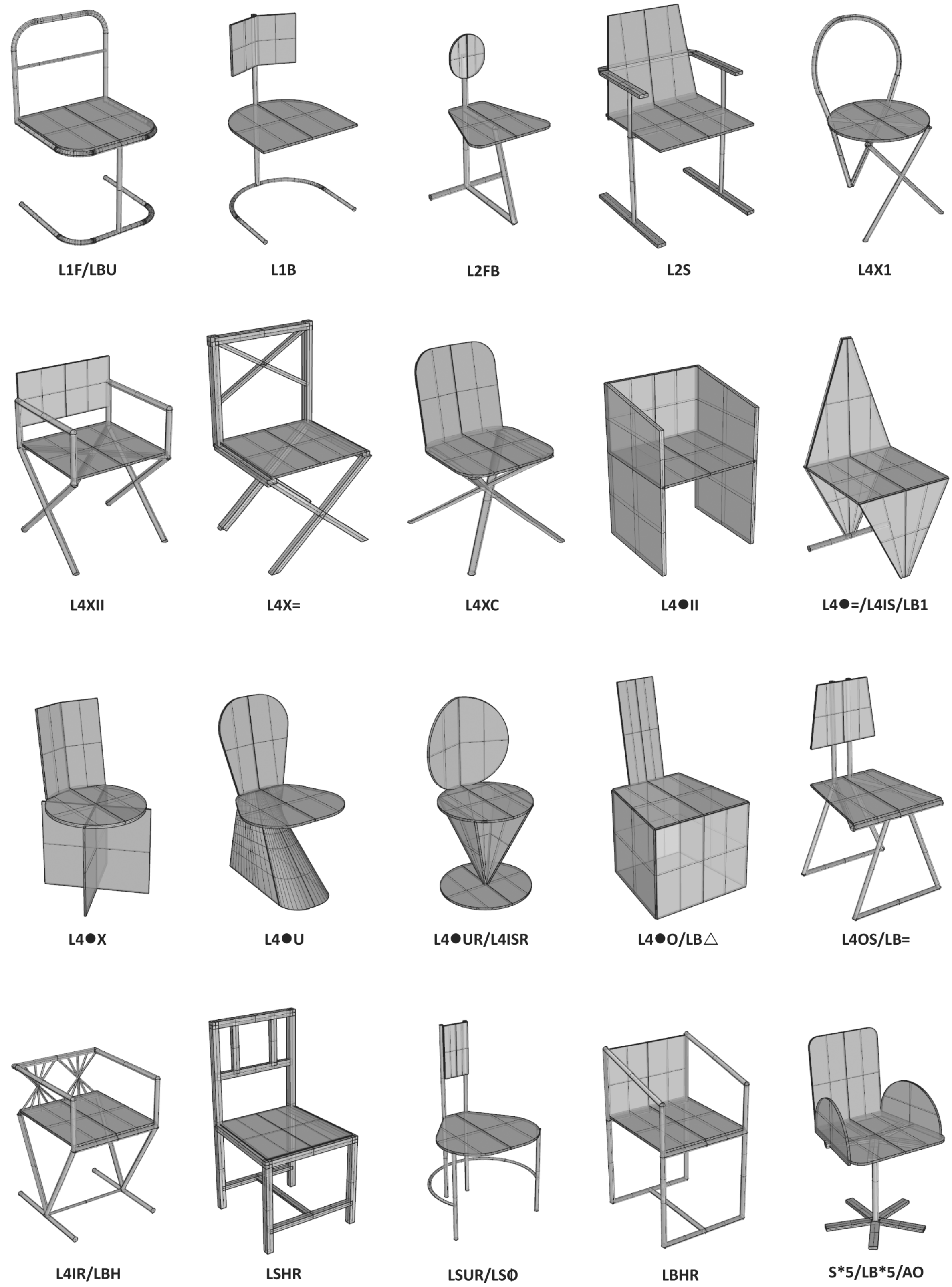


Fig. 6.17 New design types generated in ChairDNA

6.5.3 Design Collections

This section presents design collections. Although directed to generate multipurpose chairs, ChairDNA can also generate stools and side tables. **Fig. 6.18** illustrates three examples of collections: (1) *Tulip:* is a reproduction of an existing collection, including a chair (from the ICG corpus), an armchair, a stool and a side table. The collection also contains dining and coffee tables, but those are currently irreproducible by ChairDNA. (2) *Antelope:* comprises new designs within an existing collection (of an armchair from the ICG corpus): an armless chair, a stool and a table. The existing collection includes a bench, irreproducible by ChairDNA. (3) *C:* is an entirely original collection, created by the developer. The name of the collection was inspired by the various C-shapes observable in the designs and by the Continuity of the tubular frame.

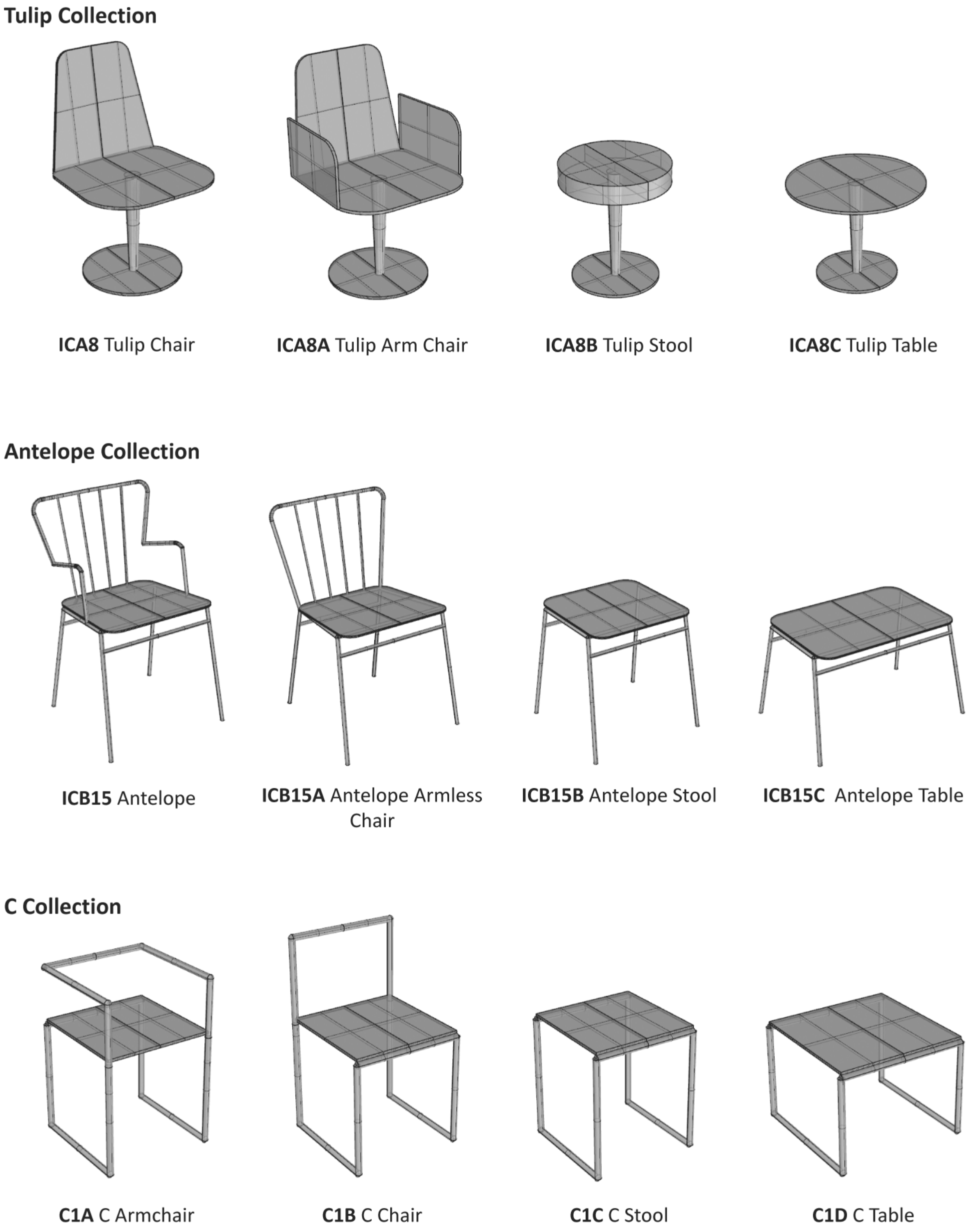


Fig. 6.18 Design collections generated in ChairDNA

6.5.4 Random Designs

The designs presented so far were all generated by the developer using ChairDNA. This section concerns designs automatically randomly generated by ChairDNA. The intervention of the human user comes down to triggering the generation process. **Fig. 6.19** displays 15 examples of random designs. The labels indicate the random seed (S) and the iteration step (I).

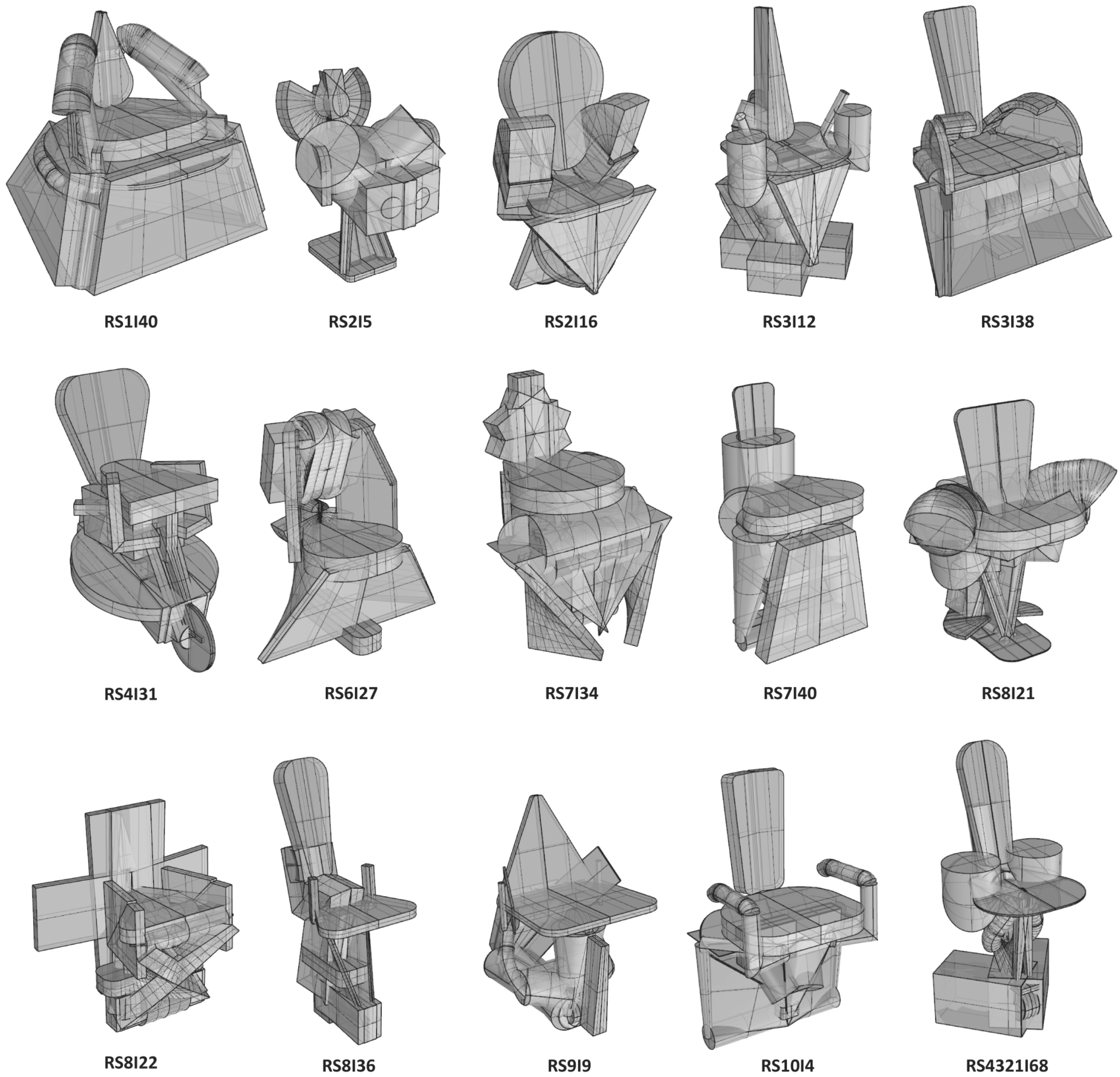


Fig. 6.19 Random designs generated by ChairDNA

6.6 Tests

ChairDNA was evaluated in terms of its generative capabilities, according to the descriptive, analytic, and synthetic tests (Stiny & Mitchell 1978). The tests were originally defined for SGs, but can be applied to analytic generative systems:

1) *Descriptive test*: evaluates whether a system is able to generate designs from the corpus;

2) *Analytic test*: evaluates whether a system is able to generate existing designs that are not from the corpus but belong to the language;

3) *Synthetic test*: evaluates whether a system is able to generate new designs that belong to the language.

The descriptive and analytic tests can be further refined, to include the *completeness test* (Garcia & Menezes Leitão 2018). This test evaluates the extent to which a generative system is able to generate existing designs. This test is applicable to a set of designs (A) which are aimed to be reproduced by a generative system (B) with a given shape abstraction level (C). The designs of A must belong to the language defined by B. The test comprises the following steps:

1) Determine the number of Reproducible Features (*Fr*) of a design of A (A1), i.e., the features of A1 which are reproducible by B;

2) Determine the number of Irreproducible Features (*Fi*) of A1, i.e., the features of A1 which are not reproducible by B but are part of the set C;

3) Determine the completeness level of A1, given by the formula $Fr / (Fr + Fi)$. The result is a value between 0 and 1; if the result is 0 it means that no feature of A1 is reproducible by B; if the result is 1 it means that A1 is fully reproducible by B;

4) Determine the completeness level of all the designs of A, by repeating the previous three steps;

5) Determine the completeness level of B, given by the arithmetic mean of the completeness levels of the designs of A. The result is a value between 0 and 1; if the result is 0 it means that B is unable to reproduce any design within the language; if the result is 1 it means that B is capable of anticipating any design within the language.

The descriptive, analytic and synthetic tests were applied to ChairDNA, considering the designs illustrated in the former section. The results of the tests are detailed below.

Descriptive Test

ChairDNA is able to generate designs from the corpus, with a precision of **0.94**. The test considered the generation in ChairDNA of the 37 designs from the corpus; including 5 Daciano Corpus designs (**Fig. 6.10**), 5 Jasper Corpus designs (**Fig. 6.11**), 2 Thonet Corpus designs (**Fig. 6.13**), and 25 Iconic Corpus designs (**Fig. 6.15**). The details of the descriptive test, including the description of the reproducible and irreproducible features and the calculation of the completeness level, are available in **Appendix 6.F.1.**

Despite the system being based on the analysis of the corpus, there are still some irreproducible features. These are related to three main issues. (i) Firstly, there are dimensions in the designs that do not fit the parametric ranges (e.g. the overall width of the chair **214**). When this occurred, the dimension was adapted in order to fit the range, selecting either the minimum or the maximum value of the range. (ii) Secondly, there are missing parameters within the shape abstraction level defined for the system (e.g. Back Upright Taper Ratio). Features related to a higher shape detail were not considered (e.g. panel mesh and panel border). (iii) Lastly, some bugs in the chair geometry were verified (e.g. the Back Splat orientation in the **Wishbone** chair).

The descriptive test applied to the MCG would provide a different result, since MCG supports multiple applications of the same part, unlike ChairDNA, which only supports multiple seat and back inner rails. Therefore, four designs would present a higher completeness level: **DKR** (containing two Radial Stretchers), **Superleggera** (containing two Side Stretchers), **S** (containing two Front Legs), and **RCP2** (containing two Front Legs and two Back Legs).

Analytic Test

ChairDNA is able to generate (or explain) existing designs, which do not belong to the corpus but belong to the language, with a precision of **0.90**. The test considered the generation in ChairDNA of the 9 existing designs of the control group, including 1 Daciano Existing design (**Fig. 6.10**), 1 Jasper Existing design (**Fig. 6.11**), 1 Thonet Existing design (**Fig. 6.13**) and 6 Iconic Existing designs (**Fig. 6.16**). The test was not applied to stools, since these designs not belong to the main language regarded by ChairDNA.

The description of the reproducible and irreproducible features is displayed in **Appendix 6.F.2**, and the calculation of the completeness level is shown below in **Table 6.3**. According to the analytic test, ChairDNA can reproduce 0.90 (90%) of the designs of the multipurpose chair class, within the abstraction level defined for the system. The standard deviation (SD) is 0.07.

Table 6.3 Analytic test of ChairDNA

	DE	JE	TE	IE						Mean	SD
	DE6	JE6	TE4	IE27	IE28	IE29	IE30	IE31	IE32		
Fr	39	44	39	29	20	37	24	21	16	30	10
Fi	4	4	5	5	7	2	0	3	1	3	2
Completeness	**0.91**	**0.92**	**0.89**	**0.85**	**0.74**	**0.95**	**1.00**	**0.88**	**0.94**	**0.90**	**0.07**

The application of the analytic test to the MCG would produce a different result, since there are designs that comprise multiple applications of the same part: **Wiggle** (including two Stretcher Panels) and **FPE** (including two Back Uprights).

The analytic test can also be independently applied to the DCG, JCG and TCG implementations. The description of the reproducible and irreproducible features and the calculation of the completeness level are also available in **Appendix 6.F.2**. The reproducible features relate the ones used by a design that fill the grammar restrictions; while the irreproducible features address all the ones that do not fill the grammar restrictions. The results of the analytic test are 0.60, 0.40 and 0.83, respectively for DCG, JCG and TCG. All the existing designs were generated by some relaxations in the grammar restrictions. Unlike the designs of the respective corpuses, the (i) **Costureira** chair includes a Side Stretcher and does not contain a Seat Front Rail; the (ii) **La Tourette** chair has a negative Back Leg Rake Angle, a Base Side Rail, and is a slat chair; and (iii) the **Muji No. 14** chair does not have Stretchers and has a Back Inner Frame Square Section.[5]

Synthetic Test

ChairDNA can generate new designs within the language, i.e., can generate original multipurpose chairs. New designs in ChairDNA can regard given design styles, as previously illustrated by 2 Daciano New designs (**Fig. 6.10**), 2 Jasper New designs (**Fig. 6.11**), and 2 Thonet New designs (**Fig. 6.13**). ChairDNA can also generate designs in common and hybrid styles, as illustrated in **Fig. 6.12**.

The synthetic test was extended in order to evaluate the completeness of the system in generating design types described in **Multipurpose Chair Ontology** that are not represented by any design of the **Multipurpose Chair Sample**. ChairDNA is able to generate new design types that are not represented by any chair of the sample, with a completeness of **0.91**. The test considered the generation in ChairDNA of 20 designs which represent 30 new types (**Fig. 6.17**). The chairs of the sample contemplate 70 types, meaning that ChairDNA is able to generate 100 different types of multipurpose chairs. The description of the reproducible and irreproducible types and the calculation of the completeness level are available in **Appendix 6.F.3**. There are three types that the tool cannot generate, comprising two types with double legged-chairs and the high-backed chair. This test only considered types within the defined shape abstraction level (it did not include curved legs and connections between parts). Since MCG is able to generate chairs with double legs, the synthetic test applied to MCG gave a result of **0.94**.

ChairDNA is also able to generate new designs (and existing designs) within a design collection (**Fig. 6.18**), comprising arm and armless chairs, stools and tables. Lastly, ChairDNA can automatically generate random designs (**Fig. 6.19**). MCG is unable to generate random designs and collections comprising other designs beyond multipurpose chairs.

All the designs presented in this chapter were generated by the developer in ChairDNA (except random designs, which were automatically generated). The next chapter (**User Evaluation of ChairDNA**) presents original designs generated by design students and design practitioners.

[5] In the original TCG, the analytic test was made with the chair No. 20 (Barros 2015), but this design is no longer in production.

6.7 Discussion

ChairDNA is an implementation of the MCG. The ChairDNA design tool comprises some differences regarding the MCG, which can be advantageous, disadvantageous, or both. Regarding advantages, the generation of designs is quicker and more accurate (since the tool automatically computes rule application), the visualization is more flexible (since one can switch between different kinds of views), and the selection of which rule to apply, at a certain derivation step, is more efficient (since these rules are displayed as enabled). Because ChairDNA can work with three CAD applications, the user can select the most suitable one. Once the generation process in ChairDNA is completed, the user may proceed in editing the 3D model in the CAD application.

Concerning disadvantages, ChairDNA does not display the rules schema visually and is limited in relation to multiple applications of the same rule. For that reason, there are six designs that are differently reproduced in ChairDNA (**DKR**, **Superleggera**, **S**, **RCP2**, **Wiggl**e, and **FPE**), presenting one or two parts less than the MCG representation.

Set grammars do not support emergence derived from subshape detection, and thus comprise less ambiguity than SGs. The MCG is a set grammar, but still encompasses some ambiguity regarding rule application. However, ChairDNA removed all that ambiguity, since the implementation methodology dictated that for each rule application there is only one possible outcome. The lack of ambiguity may be regarded as positive or a negative. On the positive side, it reduces problems of efficiency (by avoiding a combinatory explosion of alternatives), utility (by avoiding some useless alternatives), and usability (by avoiding a time-consuming and unproductive selection of alternatives). However, it has been argued that the lack of alternatives somehow limits creativity. Nevertheless, the absence of ambiguity in ChairDNA did not prevent some generated designs from being unanticipated (as visible in random designs). Moreover, regardless the lack of one type of emergence, emerging meanings can be observed in the designs, such as a 'wheel' in the design **RS4I31** (**Fig. 6.19**). Emergence and creativity are inherent to the user, guiding the exploration in the large solution space presented by ChairDNA.

The MCG termination rule was not implemented in the manual generation mode of ChairDNA. The user can finish the design at any time during the generation process, and thus generate other designs beyond chairs, such as stools and tables. This feature allows the user to have more freedom of choice; however, it does not provide any information about whether the generation process is complete. On the other hand, the termination rule was implemented in the random generation mode of ChairDNA, since, without this rule, it could not distinguish the final design of being a chair, a stool, a table, or a leg, and thus would produce highly incomplete designs.

The random generation mode is a particular feature of ChairDNA. The automatic generation of designs can be useful to the user, by providing some sort of inspiration, and to the developer, by providing a generate-and-test method, where inaccurate solutions are used for debugging and for restricting the solution space. The designs generated by the random mode are still very sculptural and extravagant, as observable in **Fig. 6.19**; for the designs to become more accurate, some parametric ranges would have to be restricted. The SCG comprises rarely used features, which is a good indication of what should be excluded from the random generation mode. For instance, legs rarely have a positive spacing (they are not placed too far away from the seat) and are never too tapered (the base does not go under 50% of the top), the base dimensions do not go under 60% of the seat dimensions, and section dimensions are never too thin (under 4 mm) or too thick (above 120 mm).

The implementation of shape or set grammars is useful for testing and debugging. This was verified in the implementation of the MCG into ChairDNA; in order to be readable by the computer, the MCG rules have become more detailed and accurate.

Another topic for discussion concerns ChairDNA as an analysis tool. In section **6.5.1**, a qualitative description of the Daciano da Costa and Jasper Morrison styles was roughly made by the analysis of the restrictions of each grammar (DCG and JCG). Comparing both styles, one can conclude that the Daciano style uses much more rigid geometric shapes and proportions than the Jasper style. This may explain why DCG uses significantly fewer parameters than JCG (38% versus 62%). Because the shape abstraction level does not contemplate slight curves, a key feature of the Jasper style is not addressed. In fact, the more organic the chair, the more inaccurate the reproduction. Moreover, the style description presented by ChairDNA is highly incomplete, since it does not address materials, colours, and other features.

It is worth mentioning that both DCG and JCG could not effectively describe the designer's style. The analytic test was not successful, meaning that either (a) five designs are not enough to define a designer's style, or (b) the designer does not have a consistent style. The results of the analytic test regarding the restrictions of the DCG, JCG and TCG (section **6.6**) suggest that the higher the completeness level, the higher the formal resemblance of a design to the defined style. In fact, the **Muji No. 14** chair is the one with a higher resemblance with the respective style, while the **La Tourette** chair is the one with a lower resemblance. Meanwhile, some relaxations of the style features can be made, as long as they keep the core identity of the style.

6.8 Conclusion

This chapter presented the implementation of the Multipurpose Chair Grammar (MCG) into the digital tool ChairDNA. The process was based on a generic methodology for implementing a set grammar in a digital environment, by translating rules and parameters into user interface elements. The ChairDNA design tool was described, regarding its requirements, user interface and commands, implementation process and programming strategy. Furthermore, it was proposed a procedure for implementing specific grammars in ChairDNA. Lastly, the generative capabilities of ChairDNA were illustrated by a set of 102 designs (95 multipurpose chairs, 4 stools and 3 tables), and tested according to the descriptive, analytic and synthetic tests. This chapter regarded the fifth stage of the computational model.

ChairDNA contributes to address two shortcomings in current research on shape and set grammars implementations: (i) the lack of implementations of design grammars, and (ii) the lack of a clear implementation methodology. ChairDNA (i) efficiently replicates the 3D parametric rules of the MCG and (ii) is based on a systematically described implementation methodology. The methodology can be applicable to the implementation of other set grammars, a subject to be explored in future work.

ChairDNA also aims to contribute towards the lack of available digital tools for the concept phase of the design process. ChairDNA is intended to assist the human designer, by generating a large variety of solutions (comprising chairs from different types) within some necessary restrictions (comprising chairs which obey anthropometric standards). The tool provides a simple and easy to learn interface, which does not require specific knowledge on SGs, programming or 3D modelling. Moreover, ChairDNA highlights the rules and parameters available at each generation step, and automatically computes their application. The tool provides a manual generation mode (in which the user can generate designs from scratch or from a given template) and an automatic random generation mode.

The recommendations for future versions of ChairDNA include the following features:

1) Edit the spectrum of random solutions, including parametric ranges restrictions, stability restrictions and connectivity restrictions (ensuring that all the parts are connected);
2) Include a higher level of shape detail, by introducing further curves (e.g. other arcs and Bézier curves), and further section shapes (e.g. oval and hollow shapes);
3) Include further shape relations (e.g. the edition of the Seat shape would affect the Stretchers and Base shapes);
4) Include options for producing components (by making unions between parts) and for the alignment of solid parts;
5) Include other types of multipurpose chairs (e.g. asymmetric chairs), other types of chairs (e.g. lounge chairs) and/or other types of furniture (e.g. dining tables);
6) Include a library of materials and joints, and templates of design types;
7) Include other automatic generation modes: design styles (from a set of designs); hybrid designs (by the composition of templates); new designs within styles and optimization;
8) Include other commands beyond generation (such as analysis, simulation, evaluation, and digital fabrication);
9) Include a feature to import designs from a 3D model, by an automatic value extraction;
10) Improve the interface, by including icons, tooltips and the possibility to interact directly in the 3D model (for e.g. by dragging points).

These recommendations were both provided by the developer and by design students and practitioners who evaluated the tool, as it will be described in the next chapter.

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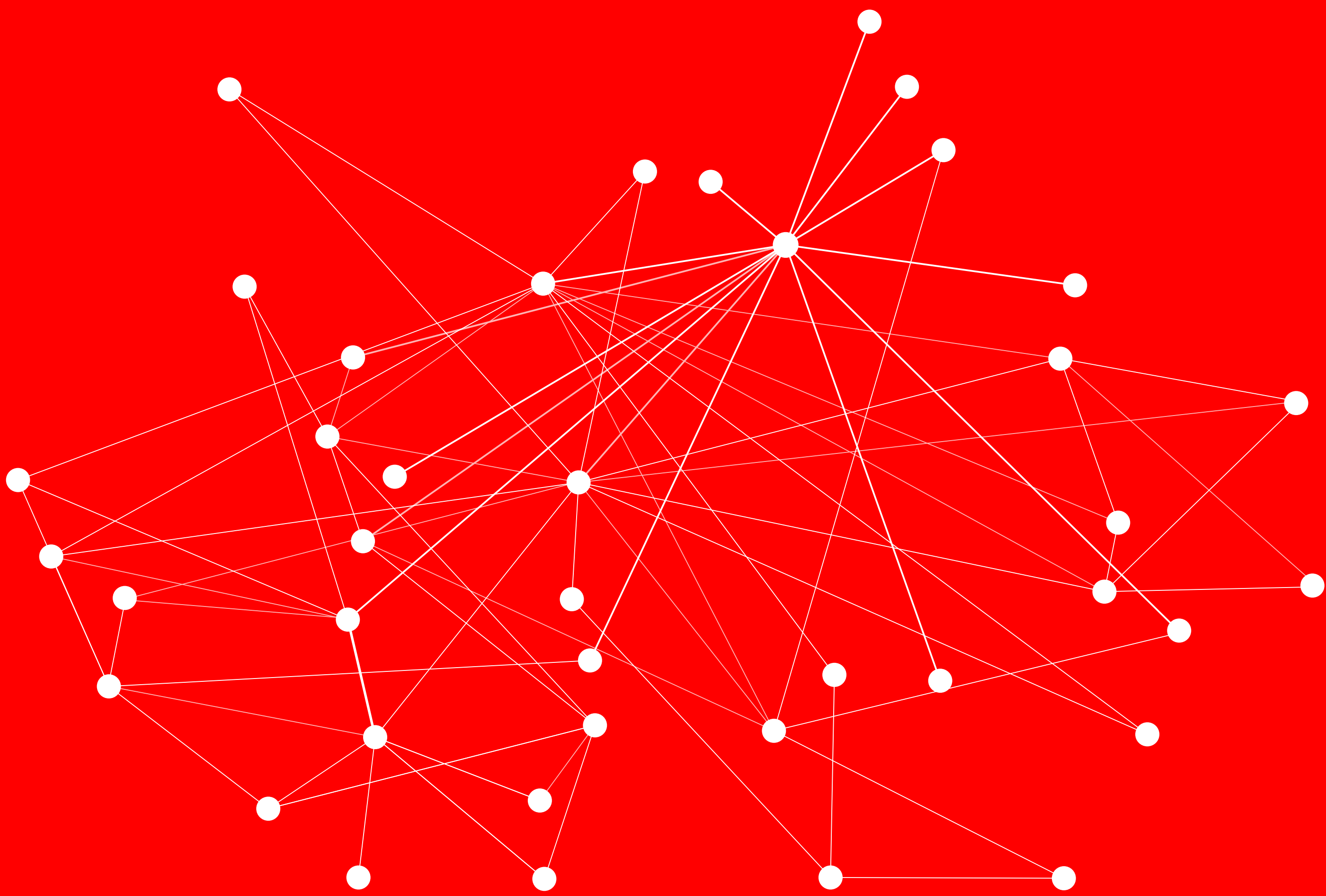
6.10 Appendixes



User Evaluation of ChairDNA

7

7 USER EVALUATION OF CHAIRDNA

The evaluation of a tool by its potential users is one of the most effective means of ensuring its usability and usefulness. The ChairDNA design tool was evaluated by two distinct types of end users, with different levels of design expertise. A first evaluation was made to ChairDNA 1.1 by design students, and a second evaluation was made to ChairDNA 1.2 by design practitioners. For both evaluations, the main task was to design a multipurpose chair, using the tool. The usability tests included different methods, such as observation, think-aloud protocol, interviews and questionnaires. The participants successfully accomplished the task, and overall considered the tool as a valuable aid in the concept phase of chair design. Moreover, they provided important insights for the development of ChairDNA.

7.1 Introduction

The evaluation of software quality embrace several characteristics (ISO 2003), such as: *functionality* (whether the software successfully executes a set of functions and properties); *reliability* (whether the software performs consistently); *usability* (whether the software is useful, easy to learn and easy to use), *efficiency* (whether the software performs within an acceptable time and resource utilization), *maintainability* (whether the software is easily modifiable), and *portability* (whether the software can be installed and ran in different environments). Tests can be performed by different individuals, such as the developer, the maintainer or the user. The *usability* evaluation is crucial in ensuring software quality, and embodies tests with end users, from whom the product is designed. A definition of usability is given by ISO 9241-11:

> *"Usability of a product is the extent to which the product can be used by specific users to achieve specific goals with effectiveness, efficiency, and satisfaction in a specific context of use" (ISO 1998).*

Usability comprises five main dimensions, according to Quesenbery (2004): *effective* (how useful is the software and how accurately the users achieve their goals), *efficient* (how quickly the goals can be accurately achieved), *engaging* (how satisfying and pleasant is to use a software), *error tolerant* (how well the software prevents and recovers from errors), and *easy to learn* (how learnable is the software).

This chapter comprises the evaluation of ChairDNA, which was described in the chapter **The ChairDNA Design Tool**. The evaluation is based on the method of usability testing: an "activity that focuses on observing users working with a product, performing tasks that are real and meaningful to them" (Barnum 2011, p.13). A process of iterative testing (Barnum 2011) was followed, since ChairDNA was developed and tested on two occasions, being the product constantly improved within the results of each test. Two evaluations were made – First Evaluation

(E1) and Second Evaluation (E2) – to two different versions of the product – ChairDNA 1.1 and ChairDNA 1.2, respectively. This process corresponds to the sixth stage of the computational model detailed in the **Introduction** chapter. E1 and E2 are briefly compared below.

Study Goals: the main goal of both evaluations was to assess the usefulness and usability of ChairDNA as a design tool for the concept phase of the chair design process. Considering the participants of E1 (design students) and of E2 (design practitioners), E1 tested ChairDNA as a pedagogical design tool, while E2 tested ChairDNA as a design tool. Both evaluations comprised formative and summative aspects (Barnum 2011), since they were intended for both diagnosis and validation; however, E1 was focused on the first aspect, since its purpose was to collect user's feedback in an early development version of the product; while E2 was focused on the second aspect, since its purpose was to validate a more advanced version of the product with more expert users, using more accurate usability metrics.

Methods: the methods employed in E1 and E2 usability tests relate to several characteristics of the testing sessions, as described below:

1) *Session Number and Length*: E1 comprised six sessions with an approximate length of one hour and 30 minutes, while E2 comprised ten sessions with an approximate length of 1 hour and 45 minutes. Both included an additional pilot test session.

2) *Testing Type:* (i) regarding the number of participants, E1 was a group testing (comprising multiple participants *per* session), while E2 was an individual testing (comprising one participant *per* session). (ii) Regarding the presence of a moderator, E1 comprised both moderated and unmoderated sessions, while all sessions of E2 were moderated. In both evaluations, the moderator was the product developer. Beyond conducting the test and interacting with the participants, the moderator also performed the roles of observer (observing the participants), logger (annotating observations and times), help desk (assisting the participants when they ask for help), and evaluator (analysing the results);

3) *Testing Methods*: E1 employed the methods of observation and post-task interview (during the test), and post-test online questionnaire (after the test). E2 applied the methods of pre-test interview (before the test), observation and think-aloud protocol (during the test), and post-test online questionnaire (after the test). The questions of both post-test questionnaires were based on two usability questionnaires: SUS – *System Usability Scale* (Brooke 1996) and USE – *Usefulness, Satisfaction, and Ease of use* (Lund 2001). Regarding the recording methods, both evaluations employed screen capture and/or recording, photographs, and notes. The tests were conducted in Portuguese, since it was the participant's mother tongue; however all the scripts and results displayed in the present document were translated into English, for clarity;

4) *Task*: the task proposed to the participants was to design a multipurpose chair, with the aid of ChairDNA. The required deliverables were, for both evaluations, the 3D digital model of the final solution; and for E1, additionally, a 3D printed scale model;

5) *Test Environment*: the testing sessions were both conducted at the participant's workplace, which in E1 comprised the same place (the student's school), while in E2 contemplated different places (the designer's workplaces). The sessions were carried out according to the field testing method, being the moderator and the participants physically in the same place, which reduces the risk of unexpected technical occurrences (such as internet connection problems inherent to remote testing methods);

6) *Test Equipment*: the accomplishment of the task required a computer. In E1, the participants could decide whether to use their own laptop or the school's desktops. In E2, the moderator's laptop was used, in order to standardize the conditions and eliminate the installation setup time;

Product: the product evaluated in E1 was ChairDNA 1.1, while in E2 was ChairDNA 1.2.

Participants: E1 and E2 comprised different group sizes and different levels of design expertise. Nineteen novice users participated in E1, and ten advanced users participated in E2. No participant had previous experience with the product.

There is no consensus regarding the minimum participant group size for a usability study, since it depends on the characteristics of the experiment, the goals, the participant's expertise, time and budget restrictions, and so forth (Macefield 2009). Until the 1990s, usability studies followed the rules of empirical research experiments, which required a minimum of 30 participants (Barnum 2011). Later on the opinions diverged: (i) for qualitative findings, Nielsen & Landauer (1993) suggested that 5 participants were enough to obtain 85% of the usability problems, while Faulkner (2003) argued that 10 participants would reveal at least 80% of the problems. (ii) For quantitative findings, Barnum (2011) advocated that 12 to 20 participants should be employed to obtain descriptive statistic results (concerning the participants group and not the entire population). From the analysis of several studies, Macefield (2009) suggested the following baseline ranges: (i) 5-10 for qualitative findings (such as problem discovery); and (ii) 10-12 for quantitative findings (such as comparative studies). According to the author, 10 participants ensure the discovery of 82% of qualitative problems and produce statistically significant findings. Based on this assumption, a minimum of 10 participants was established for the evaluations, in order to reveal both qualitative and quantitative findings.

Results and Discussion: several findings were retrieved from various sources (interviews, questionnaires, observation notes, think-aloud comments and performance data). The results will be presented in both absolute and relative values, in the format (Number of participants; Percentage); or in the format (Mean; Standard Deviation). Quantitative results from the pilot tests were not statistically considered, since relevant changes were made in the test scripts. The evaluations also resulted in a set of recommendations for future versions of ChairDNA.

In the following sections, both evaluations will be detailed along the previously mentioned guidelines (*study goals*, *methods*, *product*, *participants*, and *results/discussion*).

7.2 First Evaluation

The first evaluation (E1) comprised the test of ChairDNA 1.1 by design students. The study was conducted between 19th November 2014 and 11th February 2015.

7.2.1 Study Goals

The main goals of E1 were the following:

1) Evaluate the usefulness of ChairDNA 1.1 as a pedagogical chair design tool;
2) Evaluate the usability of the ChairDNA 1.1 interface;
3) Evaluate the accuracy of ChairDNA 1.1 in reproducing the participant's intentions;
4) Obtain useful inputs for the development of ChairDNA 1.2;
5) Test the evaluation method, in order to perform a second evaluation with more advanced users.

7.2.2 Method

The E1 experiment comprised six testing sessions (beyond the pilot test): four moderated (of around one and a half hours each, with multiple participants) and two unmoderated. The employed testing methods were observation, interviews and questionnaires. The task comprised the development of a design from an inspiration or a concept previously formalized, with the optional aid of ChairDNA 1.1. The final solution should be presented in the format of a 3D digital model and a 3D printed 1/8 scale model. The tests took place at the student's classroom at the Faculty of Architecture of the University of Lisbon. The participants used either their own laptop or the classroom's desktops. The sessions are described below:

1) *Presentation and demonstration of ChairDNA* (19th November 2014): the moderator presented an overview of the research project, made a brief demonstration of ChairDNA 1.1, and delivered the task briefing (available in **Appendix 7.A.1**) to the participants;
2) *Installation and first experiments with ChairDNA* (21st November 2014): after watching a second demonstration of the program, the participants installed ChairDNA 1.1 and made their very first experiments within the tool;
3) *Experimenting and designing with ChairDNA* (3rd December 2014): the participants used ChairDNA 1.1 in a preliminary exploratory approach. The testing method employed in this session was structured observation (Martin & Hanington 2012), comprising a systematic collection of data through coded notes and photographs. The moderator individually interacted with the participants and recorded their difficulties,

suggestions and software bugs; while the participants recorded or captured the computer's screen;

4) *Designing with ChairDNA* (4th December 2014 – 6th January 2015): the former moderated session at the classroom was followed by other unmoderated sessions undertaken by the participants to complete their designs;

5) *Participant's presentations* (7th January 2015): the participants individually presented their work in a group session. They delivered the 3D digital model, the printed scale model, and a description of the process (through texts, screen records and/or screen captures). At the end of each presentation, a short structured interview of ten questions (script in **Appendix 7.A.2**) was conducted with each participant;

6) *Post-test Questionnaire* (9th January 2015 – 11th February 2015): in this unmoderated session, participants were asked to fill in an online questionnaire (script in **Appendix 7.A.3**), with closed- and open-ended questions, about their experience and impressions regarding ChairDNA 1.1. Not all the participants filled in the questionnaire; the response rate was about 79% (15 filled questionnaires among 19 participants). In the subsequent section **7.2.5**, the findings addressing this source will be indicated as incomplete (INC).

Pictures of sessions 3 and 5 are displayed below in **Fig. 7.1**.

Fig. 7.1 E1 session's pictures: session 3 on the left and session 5 on the right (author's photos)

7.2.3 Product

The evaluated product in E1 was ChairDNA 1.1 (described in the chapter **The ChairDNA Design Tool**). The application could be used either with AutoCAD or Rhinoceros.

The product in the pilot test was ChairDNA 1.1.0. The version of the pilot test was improved to the E1 tests, because there was a critical bug in ChairDNA 1.1.0 that disallowed 3D printing, and there were some imperceptible acronyms in the names of the commands.

7.2.4 Participants

The group of participants of E1 was composed by 19 students from an intermediate design class. The students were at the 3rd year of the undergraduate Design course of the Faculty of Architecture of the University of Lisbon. The experiment took part of the programme of a course unit entitled “Parametric Modelling and Digital Prototyping in Design”. The list of participants can be consulted in **Appendix 7.A.4**, and the consent forms signed by the participants are available in **Appendix 7.A.5**.

The participants profile was analysed in terms of their (i) demographic profile, (ii) past experience with CAD software, and (iii) chair design expertise.

The participant's demographic profile was analysed according to their gender, age, and education. The participants, aged between 20 and 33 (with a mean age of 22), were mostly female (17 participants, corresponding to 89%). All the participants were undergraduate design students.

The experience of the participants with CAD software is illustrated in **Fig. 7.2**. All participants had experience with 3D modelling CAD software, since during the Design course they have learned AutoCAD (in the 1st and 3rd years), and 3ds Max (in the 3rd year). **Fig. 7.2** (top left) indicates which CAD software was most commonly used, based on the ranking mean[1]. The preferred CAD software was AutoCAD (5.0 – INC), followed by 3ds Max (3.3 – INC), SketchUp (3.1 – INC), and lastly Rhinoceros (2.3 – INC). Participants had no experience with VectorWorks.

Regarding the design phase (**Fig. 7.2**, top right), CAD software was mostly used in the development phase (42% – INC), followed by the production (29% – INC) and the detail phases (21% – INC); participants hardly used such tools in the concept phase (8% – INC) and never in the research phase. The only CAD software used in the concept phase was SketchUp (3 participants; 20% – INC). Note that participants interpreted the design phases differently (since no description of them was provided). For instance, several participants considered the rendering task as being part of the production phase.

Concerning the design tasks (**Fig. 7.2**, bottom), CAD software was mostly used for technical drawing, 3D modelling and rendering (respectively, 33%, 28% and 26% – INC); was less used for digital fabrication, ideation and communication (respectively, 5%, 5% and 3% – INC); and was never used for analysis/optimization and management tasks. The CAD software used for ideation tasks was both AutoCAD and SketchUp (each used by 1 participant; 7%).

[1] Each participant ranked the CAD software in order of preference. The raking mean is calculated by a weighted mean of the results, where the 1st choice corresponds to a weight of 5, the 2nd choice to a weight of 4, the 3rd choice to a weight of 3, the 4th choice to a weight of 2 and the 5th choice to a weight of 1.

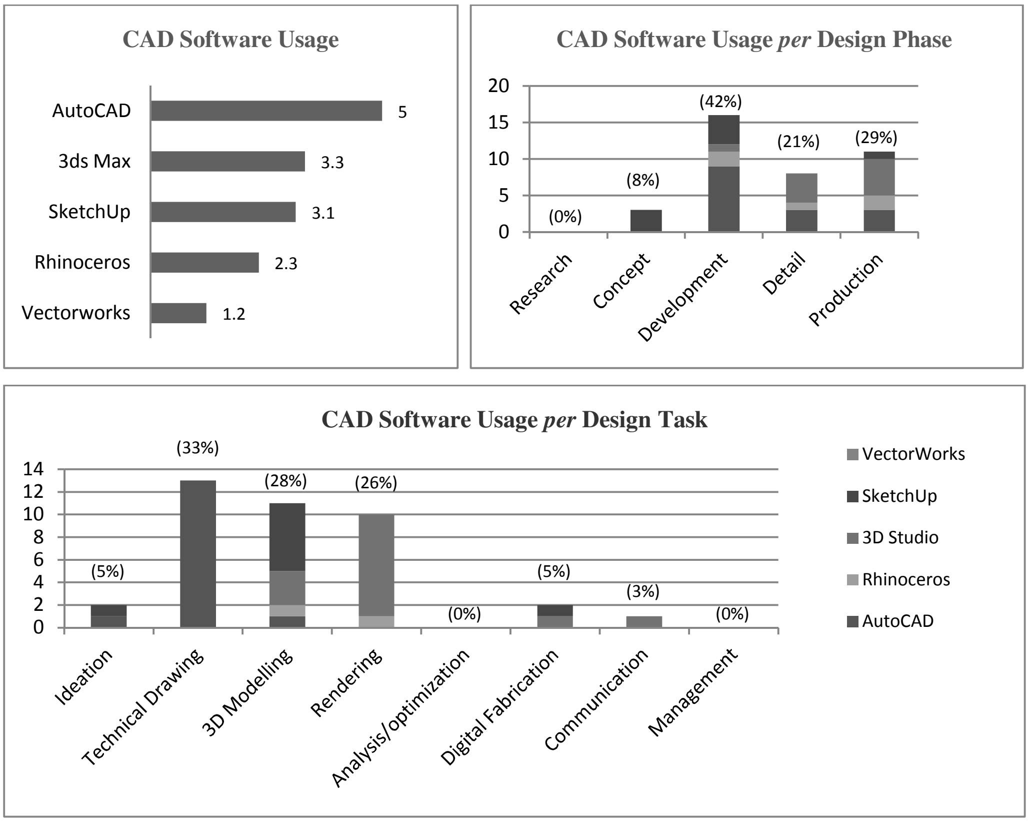


Fig. 7.2 Experience of E1 participants with CAD software (INC data)

The chair design experience of the participants was evaluated taking into account the design phase achieved for each of the following contexts: industry, design studio, design competitions and academic projects. Participants did not have any experience in industry and design studio; only one participant had experience in design competitions. They all had academic experience in chair design, obtained with two academic projects where students had to develop: (i) a scale model of a hybrid design between the chairs Red/Blue and Zig-Zag, both designed by Gerrit Rietveld (Design Museum 2009); and (ii) a full-scale prototype of an original chair.

7.2.5 Results and Discussion

The main results of E1 will be presented along the following topics: (i) task outcomes (including the resulting designs and the participant's design process), (ii) ChairDNA 1.1 usability, (iii) ChairDNA 1.1 usefulness as a chair design tool, and (iv) recommendations for future versions.

Task outcomes

The task outcomes were twofold: (i) the resulting designs; and (ii) the design process (from the initial idea until the final solution). The digital models of the final solutions are illustrated in **Fig. 7.3** (the ones greyed out were generated without using ChairDNA 1.1). The designs are labelled for future cross-reference (in bold).

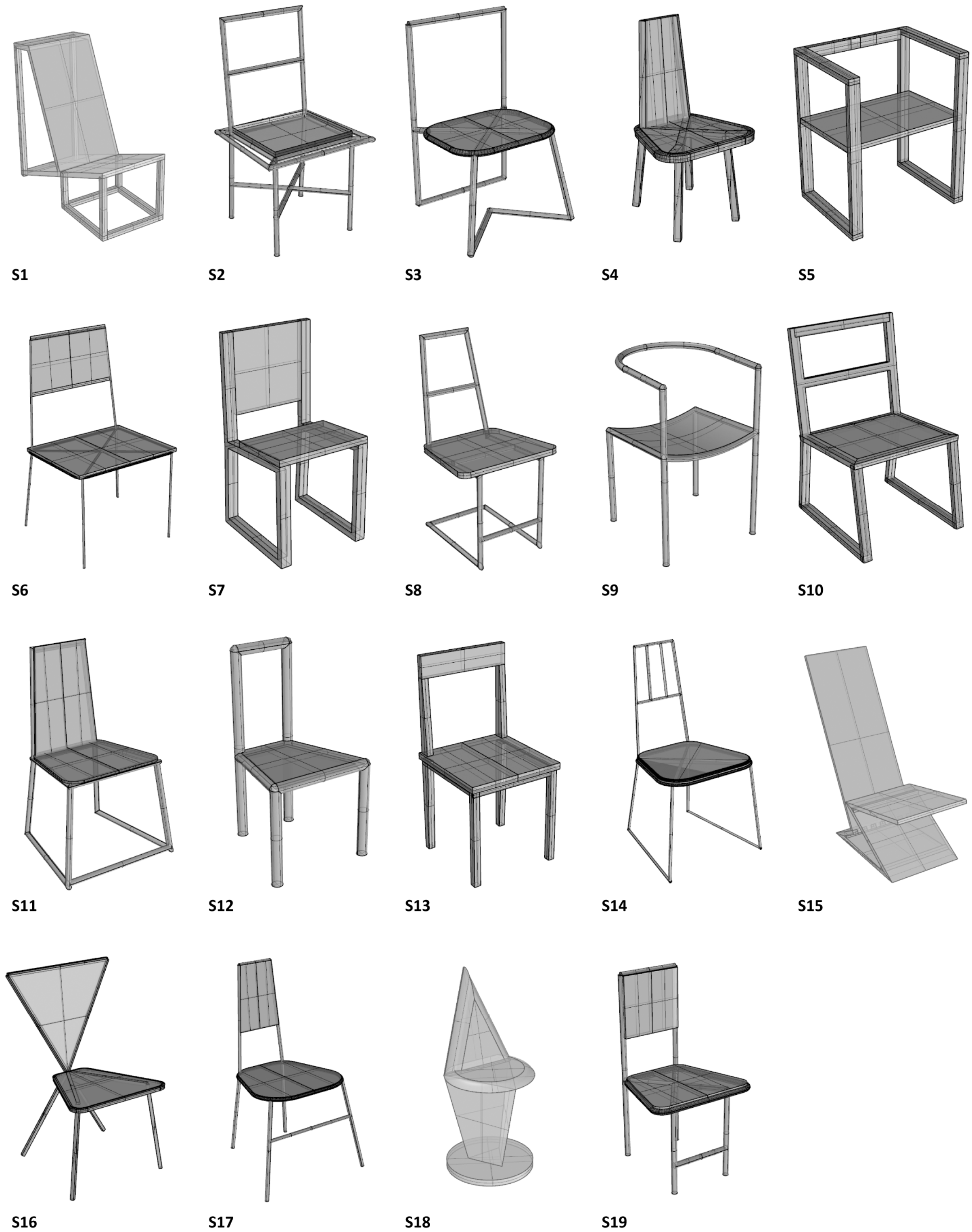
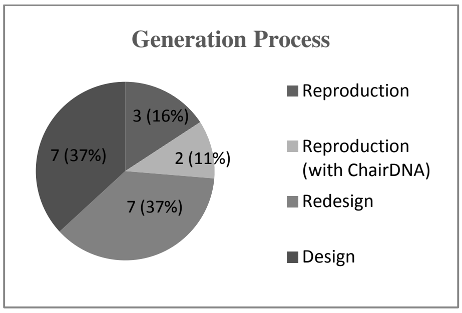


Fig. 7.3 E1 resulting designs (designs greyed out: generated without the aid of ChairDNA 1.1)

The participants were asked to previously formalize an inspiration or an initial idea. The initial concepts (displayed in **Appendix 7.A.6**) comprise participant's designs (9; 47%), chairs from other designers (8; 42%), and written descriptions – the case of the design **S14** (1; 5%). The design **S2** did not encompass any formalized inspiration (1; 5%). The task of E1 was to develop a design inspired by the initial concept, with the optional aid of ChairDNA 1.1.

Fig. 7.4 displays the main results of the participant's design process. The participants adopted three main processes (**Fig. 7.4**, left): (i) reproduction of the initial idea (5; 26%) – designs **S1**, **S9**, **S13**, **S15**, and **S18;** (ii) redesign of the initial idea (7; 37%), and (iii) design from scratch, disregarding the initial idea (7; 37%). From the participants that reproduced the initial idea, only two did it with the aid of ChairDNA 1.1 (11%) – corresponding to the designs **S9** and **S13**.

The non-reproduction of the initial idea (**Fig. 7.4**, right) was mainly justified by both ChairDNA limitations and exploration of the solution space (7; 50%), being the exploration the main reason for 5 participants (36%) and the limitations the main motive for only 2 participants (14%). The limitations mentioned by the participants were related to missing shape parameters (e.g. curves, angles, and number of parts).



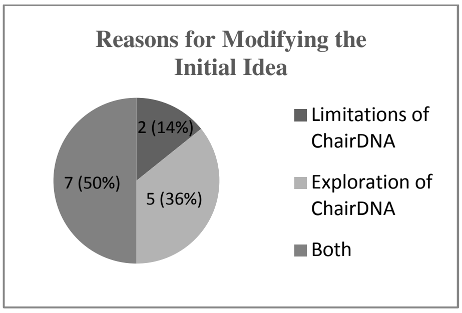


Fig. 7.4 Main results of the design process used in the E1 task

The usage of ChairDNA 1.1 in achieving the final solution is presented in **Fig. 7.5** (left). Most students used ChairDNA 1.1 (16; 84%) but only a small percentage of them used it exclusively, without editing the model in CAD software (3, 16%). The designs generated exclusively in ChairDNA are **S3**, **S6** and **S16**. All the participants selected AutoCAD as the back-end CAD software of ChairDNA 1.1, since it was the software they were more familiar with. The adjustments made by the participants in the digital model after using ChairDNA 1.1 were caused by program bugs (in Seat and Back thickness) and program limitations in joints, section orientation, Seat and Back curvature, and Legs Taper Ratio. The CAD software used to edit the model was mostly AutoCAD (only one participant used 3ds Max).

Three participants (16 %) did not use ChairDNA 1.1, because it was not feasible to reproduce their initial idea, which comprised lounge chairs (**S1** and **S15**) or pedestal chairs (**S18**). To generate the final solution, one of these participants used AutoLISP together with AutoCAD and other two only used AutoCAD.

The students used other tools beyond ChairDNA (**Fig. 7.5**, right). Before using ChairDNA they mostly used drawing and diagrams. While participants were using ChairDNA, they employed different tools more or less evenly (note that the use of CAD software was mandatory as the ChairDNA back-end). After using ChairDNA they mostly used models (that were mandatory to print a scale model) and other CAD software (which were largely used to edit the 3D model, as aforementioned).

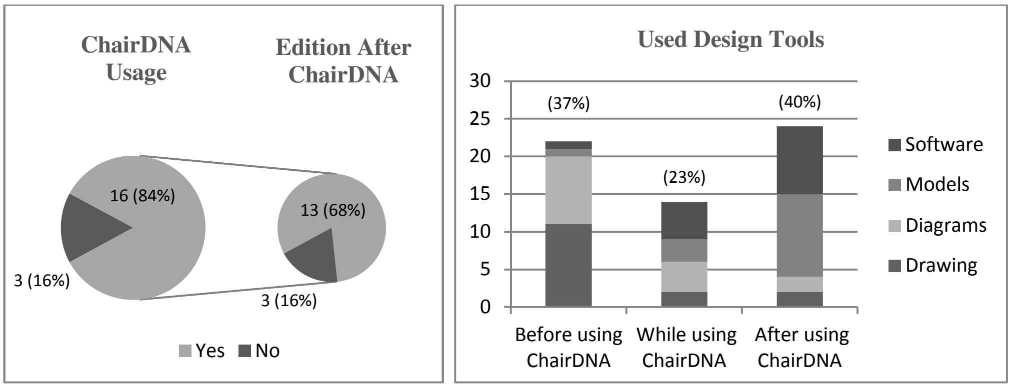


Fig. 7.5 Design tools used in E1 (on the left: ChairDNA; on the right: other tools – INC data)

The materials that the participants envisioned for the final designs are detailed in **Fig. 7.6** (left). For each of the two main parts of the chair (frame and seat/back panels), one material (from the categories: wood, metal, plastic and textile) was assigned. The preferred materials were metal (for the frame) and wood (for the seat/back panels). Most participants (11; 73% – INC) did not consider materials as a constraining factor during the generation process (**Fig. 7.6**, right). Incidentally, the choice of the material did not affect the section shape (for instance, the metal frame sections where equally round and square).

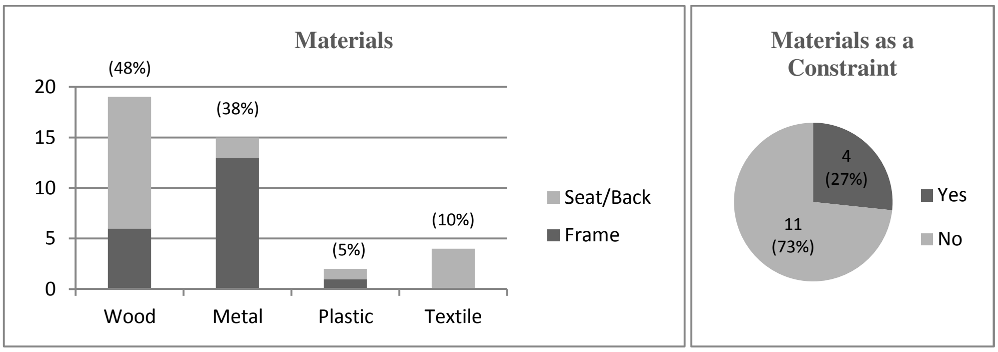


Fig. 7.6 Envisioned materials of E1 resulting designs (left) and materials as a constraint (right – INC data)

Thirteen 3D printed scale models, generated with the aid of ChairDNA 1.1, are presented in **Fig. 7.7**. Two models also generated with ChairDNA are not shown (**S4** and **S10**) because they broke during or after printing, and the design **S6** was not printed. The scale models were printed from one of the two following technologies, available at the faculty Lab: Fused Deposition Modelling technique (FDM) and 3D Printing technology (launched by Z Corporation). The majority of the participants used the former technology, since it was the cheapest option. The printers comprised some restrictions that obligated nearly half of the participants to make changes in the 3D model, mostly to increase the thickness of the frame or, in one case, to refine the union between the parts of the chair.

Fig. 7.7 Above: the solution S12 being printed; below: thirteen E1 resulting scale models (author's photos)

Other results obtained from the user test, comprising the analysis of some generation sequences and the types of resulting designs are available in **Appendix 7.A.9**.

ChairDNA Usability

The evaluation of the ChairDNA 1.1 usability and usefulness was mostly done through five-point Likert scale questions, where the lower score (1) corresponded to 'strongly disagree' and the higher score (5) corresponded to 'strongly agree'. The results are presented in the present section and the subsequent section in the format (Mean; Standard Deviation).

In general, the participants revealed a positive overall appreciation of the ChairDNA 1.1 usability (**Fig. 7.8**, left). The results are, from best to worst: ease of learning (4.27; 0.80 – INC), ease of use (3.87; 0.74 – INC), overall coherence (3.80; 0.68 – INC), user experience (3.13; 0.83 – INC), efficiency on the response speed (3.07; 1.16 – INC), and flexibility in adapting to the user needs (2.93; 0.46 – INC). The low appreciation regarding ChairDNA 1.1 efficiency was justified by a poor performance, recurrent crashes, and inability of the program to save states of the solution. The ChairDNA flexibility in adapting to the user's needs was also poorly evaluated, which may be a situation to consider in future developments.

The ChairDNA 1.1 commands were positively evaluated (**Fig. 7.8**, right), in relation to their terminology (4.13; 0.83 – INC), distribution in the interface (4.20; 0.77 – INC), quantity (3.13; 0.74 – INC), and activation sequence (4.13; 0.64 – INC). The dissatisfaction of the users regarding the quantity of available commands was sustained by many suggestions for the inclusion of other features in ChairDNA.

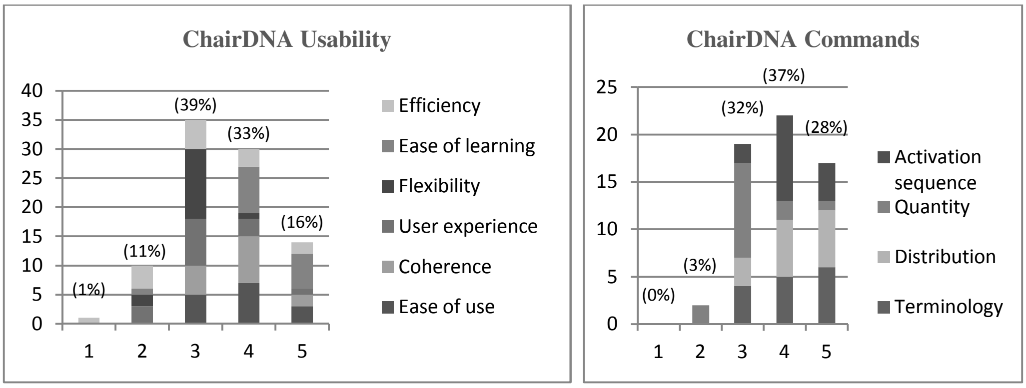


Fig. 7.8 ChairDNA 1.1 usability results (INC data)

ChairDNA Usefulness

The participants provided a positive appreciation of the utility of ChairDNA 1.1 as a design tool (**Fig. 7.9**). They claimed that ChairDNA limits decision-making (3.67; 1.05 – INC), though it had also allowed the emergence of solutions that they did not consider at the beginning (3.40; 0.83 – INC). The participants considered the generation sequence provided by the tool adequate (3.60; 0.51 – INC), but expressed a not very satisfactory opinion about the achieved solution (3.33; 0.62 – INC), arguably due to the low level of shape detail. Participants took a neutral position about the ability of the tool to provide new knowledge about the shape and structure of chairs (3.13; 0.92 – INC). The utility of ChairDNA in the design process was positively evaluated (3.80; 0.86 – INC), and the participants were willing to use the tool in future projects (3.73; 0.80 – INC).

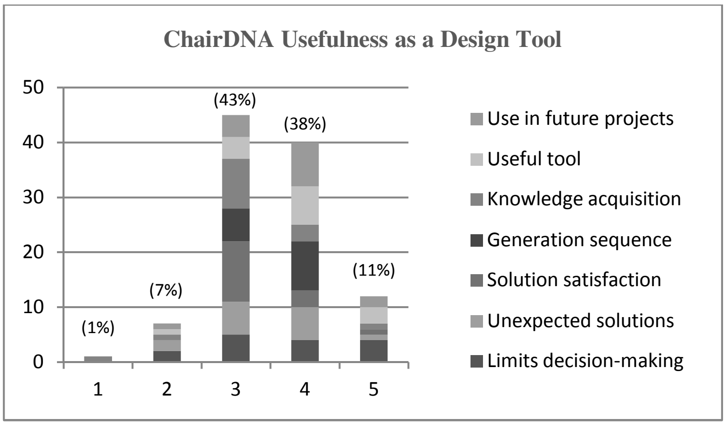


Fig. 7.9 ChairDNA 1.1 usefulness results (INC data)

The participants also gave some input regarding strengths and weaknesses of ChairDNA 1.1. On the strengths side, the participants emphasized the speed and ease in generating the basic structure of a design using ChairDNA. Two participants mentioned the ability of ChairDNA to generate unexpected solutions and one participant commented on the utility of having anthropometric guidelines. The participants also highlighted the ease of use of the tool, which allows it to achieve a large audience. Some positive aspects are summarized in the following comment:

> *"It is possible to generate a chair in few minutes. The program is very intuitive, being able to be used by anyone. It provides ideas that we wouldn't have thought of at the beginning, but which may actually be a good solution" (participant S7)*

On the weaknesses side, the least appreciated aspects of ChairDNA 1.1 were the lack of features concerning shape detail (regarding joints and curves), the lack of a save command and the low performance of the program. Other negative points relate to the inability to enter numerical values and the incompatibility with the Mac OS X operating system. Lastly, the limitation of the tool regarding the types of designs that can be generated was also criticized:

> *"[ChairDNA] is only focused on the generation of dining chairs" (participant S15)*

ChairDNA Recommendations

The participants provided a set of suggestions for further developments of ChairDNA, based on the negative points aforementioned. They strongly recommended the inclusion of a save command, the edition of the slider values through numerical input, and the improvement of the program performance. Other important recommendations regard the introduction of further curves and joints between the parts, which correspond to the main adjustments the participants made in the 3D model after using ChairDNA. Some minor proposals concern the introduction of new variables to control the shape (e.g., Arms angles and Legs taper ratio), whereas fewer participants indicated materials and structural analysis as a priority. Three participants suggested the compatibility of ChairDNA with the Mac OS X operating system. Participants also recommended the inclusion other types of seats, especially stools, office chairs, and lounge chairs, but also children's chairs. Note that ChairDNA 1.1 was already capable of generating stools.

Participants provided a total of 40 recommendations. From these, 2 (from the pilot test) were implemented in ChairDNA 1.1; 29 were implemented in ChairDNA 1.2 (73%), while the remaining 9 were not implemented. The description of the implemented features can be consulted in the appendixes of the previous chapter (**The ChairDNA Design Tool**), in ChairDNA 1.1 and ChairDNA 1.2 new features lists, as well as the non-implemented features, which are available in the recommendations list. Meanwhile, the developer elaborated 58 features to be improved; therefore, the participants contributed with 41% of the recommendations. This is not a low percentage, considering that ChairDNA 1.1 was an early and very incomplete prototype.

The extended results of E1, which were summarized in this section, can be consulted in: **Appendix 7.A.7** (observation notes), **Appendix 7.A.8** (interview statistics), **Appendix 7.A.9** (user test statistics), and **Appendix 7.A.10** (questionnaire statistics).

7.3 Second Evaluation

The second evaluation (E2) comprised the test of ChairDNA 1.2 by design practitioners. The study was conducted between 26th January and 16th February 2017.

7.3.1 Study Goals

The main goals of E2 were the following:

1) Evaluate the usefulness of ChairDNA 1.2 as a chair design tool for the concept phase;
2) Evaluate the usability of the ChairDNA 1.2 interface;
3) Analyse the participant's chair design process in the light of the ChairDNA 1.2 features;
4) Elaborate a list of recommendations for ChairDNA 2.1.

7.3.2 Method

The E2 experiment comprised ten moderated individual sessions (beyond the pilot test). The employed testing methods were observation, think-aloud protocol, interviews and questionnaires. Whenever possible, the tests were conducted at the designer's work environment, in order to allow testing the product in the actual context of its use and to facilitate the acceptance of the participants, since the experiment was time-consuming and *pro bono*. Eight sessions were conducted at the participant's workplace, and two sessions were exceptionally conducted at the Faculty of Architecture of the University of Lisbon.[2] For the experiment, all the participants used the moderator's laptop. The sessions were divided into three stages:

1) *Pre-test interview*: the moderator interviewed the participant and filled the responses online, while the audio was being recorded. The method of structured interview was employed to collect information about the participant's profile and background, before introducing the product. The interview script can be consulted in **Appendix 7.B.1**.
2) *User test:* in this stage, the participants had to accomplish four tasks (which will be later described) using ChairDNA 1.2. Before the tasks, the participants visualized a quick start tutorial video (available in the appendixes of the previous chapter). Direct and indirect observation techniques (Gediga, Hamborg & Düntsch 2002) were used. The former was employed during the task (in real-time), along with think-aloud proto-

[2] Corresponding to the sessions of the participants P5 and P6 (**Appendix 7.B.4**). In these cases, the participant's professional activity at the time did not contemplate chair design.

col (Barnum 2011), which encouraged the participants to share their thoughts while working with the product. The latter was undertaken after the session, through the visualization of the screen recordings of the sessions. Moreover, after each task, immediate feedback concerning the ease in achieving the goals was collected through a post-task questionnaire. The script of the user test is available in **Appendix 7.B.2**.

3) *Post-test questionnaire*: the participants filled an online questionnaire, composed by closed and open-ended questions concerning the test and the participant's impressions about ChairDNA 1.2. The questionnaire script can be consulted in **Appendix 7.B.3**.

The total length of each session was approximately one hour and 45 minutes. The first stage had an average duration of 35 minutes, the second stage of 50 minutes, and the third stage of 20 minutes. Some pictures of the sessions are depicted in **Fig. 7.10**.

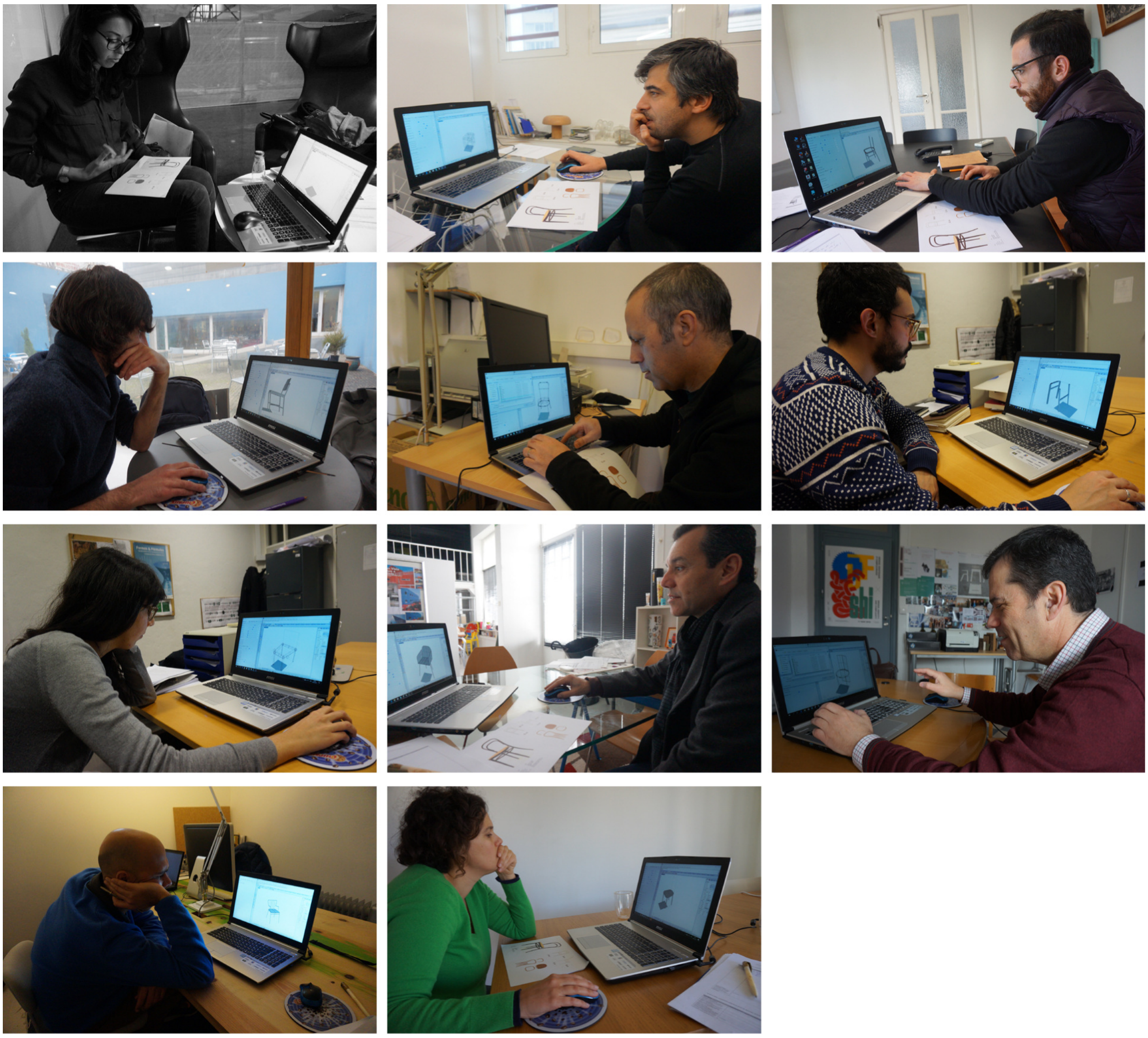


Fig. 7.10 E2 session's pictures; pilot test on the top left (author's photos)

7.3.3 Product

The evaluated product in E2 was ChairDNA 1.2 (described in the chapter **The ChairDNA Design Tool**). For this purpose, ChairDNA had to be necessarily used with Rhinoceros.

7.3.4 Participants

The group of participants of E2 was composed by 10 Portuguese design practitioners, with recognized experience in chair design. The participants list is displayed in **Appendix 7.B.4**, while the consent forms are available in **Appendix 7.B.5**. The selection of the participant's group comprised three main criteria:

1) The study population was defined upon the target population of ChairDNA, which contemplates chair designers. This population was narrowed to Portuguese chair designers, according to the convenience sampling method Marshall (1996); because the sessions were conducted on the field, a criteria of proximity had to be adopted, in order to save resources. Consequently, the study characterizes the chair design of a specific region, which, although is not the main focus of the study, may be considered a contribution of the same.

2) Beyond the regional criteria, the study population only addresses designers with recognized work in the chair design domain. The study population was extracted from five sources, comprising winners of two international design competitions (Branco 2012; Praquin 2013) and authors represented in three Portuguese design exhibitions (Coutinho 2015; Parra 2011; Experimentadesign 2011). The study population is composed by 31 individuals, and the database can be consulted in the **Sample** chapter.

3) From the study population, ten individuals were available to participate in the study (32%). According to Macefield (2009), this is an acceptable number to gather significant qualitative and quantitative results. Incidentally, the participants group comprise a heterogeneous representation of the study population, regarding gender, age, workplace district, and employment type.

The participants profile was analysed in terms of their (i) demographic profile, (ii) CAD software skill level and (iii) expertise on chair design.

The demographic profile of the participants is illustrated in **Fig. 7.11**, including data related to: (i) the workplace city/town and district, (ii) gender, (iii) age, (iv) employment, and (v) education level. The workplace of the participants was geographically distributed along the following districts: Lisbon (6), Porto (2), Aveiro (1), and Leiria (1). Participants were mostly male (8 participants; 80%) and were aged between 26 and 56 (with a mean age of 39), being the majority in their 30s. Regarding the employment type, four participants worked in a design studio, two accumulated the functions of teacher and designer, one worked in a furniture manufacturing company (Adico[3]), one was a freelance designer, one worked in an advertising agency and other in a technology company. The participant's education level contemplated the following degrees: all participants were graduated (nine in Design and one in Architecture); four also held a Master degree (three in Design and one in Drawing) and two also held a PhD degree (in Design).[4]

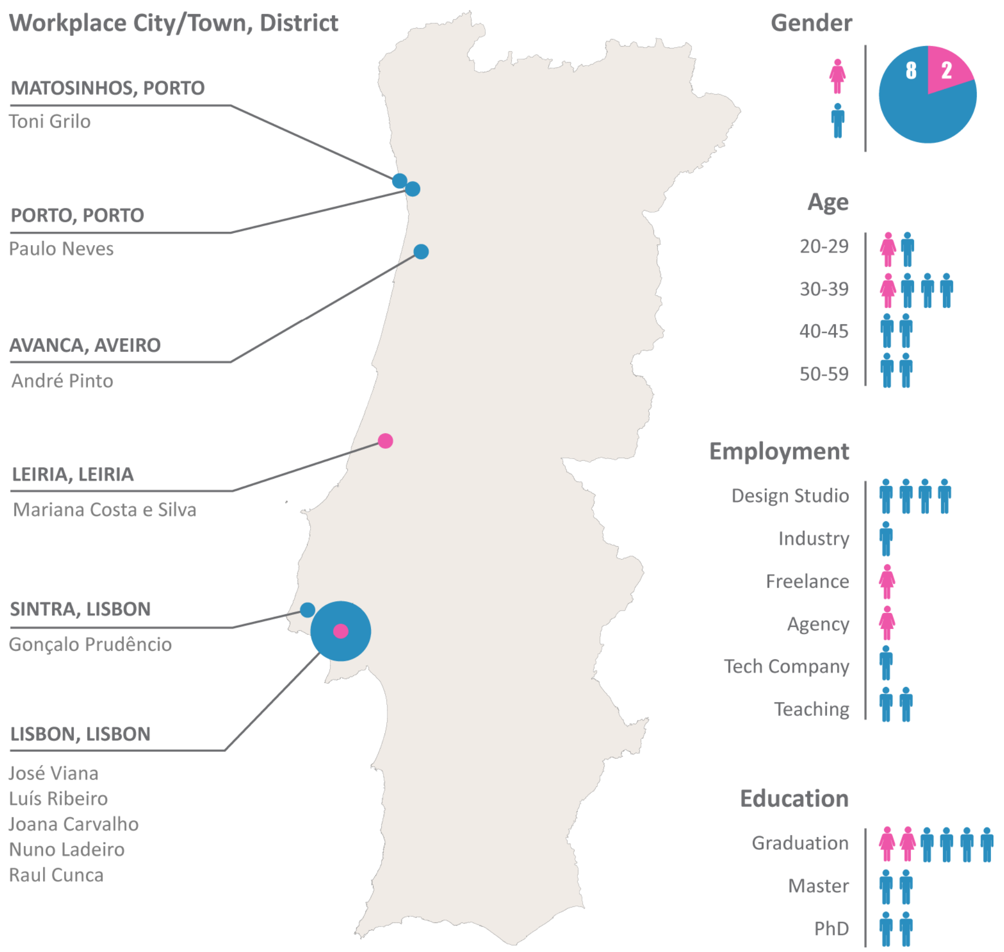


Fig. 7.11 E2 participant's demographic profile

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[3] Adico's website: http://www.adico.pt

[4] The participant's academic degrees were undertaken at the following seven institutions: Faculty of Architecture – University of Lisbon (*Faculdade Arquitectura – Universidade de Lisboa*); *Faculdade Belas-Artes – Universidade de Lisboa*; *Universidade Lusíada* (Lisbon); *Universidade de Aveiro*; *Escola Superior de Tecnologia e Gestão – Instituto Politécnico Viana Castelo*; *Domus Academy* (Milan); and *École Boulle* (Paris).

The design expertise of the participants was assessed by the years of professional experience. To that end, it was employed a classification commonly used in job ads: junior or novice designer (less than 3 years), midlevel (3-5 years), and senior or expert designer (more than 5 years). The participants were almost all expert designers (9; 90%), being only one participant in the midlevel category (10%).

Eight participants had experience with 3D CAD software (80%). The remaining two were indirect CAD users, as they relegated the 3D digital modelling tasks to their collaborators. Some participants were experienced in parametric modelling but none were familiar with shape grammars. **Fig. 7.12** summarizes the participants experience with CAD software.

Fig. 7.12 (top left) summarizes the designer's preferences regarding CAD software, indicating the ranking mean[5]. SolidWorks was prominently on the top of the preferences (3.3), followed by AutoCAD (1.5), Rhinoceros (1.2), 3ds Max (0.8), SketchUp (0.5) and lastly Cinema 4D (0.3).

Participants used 3D CAD software quite regularly among the all design phases (**Fig. 7.12**, top right). The phases where this kind of tools were used more intensely was the development (25%), detail (24%) and production (24%) phases. These tools were less used in the concept phase (20%) and little used in the research phase (8%). The participants used different CAD software in the concept phase (SolidWorks, SketchUp, 3ds Max and Rhinoceros).

The usage of CAD software among design tasks (**Fig. 7.12**, bottom) was, from highest to lowest ranking: 3D modelling (19%); technical drawing (16%); rendering and ideation (13% each); analysis/optimization, digital fabrication and communication (12% each), and management (3%). For ideation tasks, participants also used diverse CAD software, although different from what they have indicated for the concept phase (SolidWorks, SketchUp, Rhinoceros and AutoCAD).

All participants, even those who did not directly use 3D CAD software, recognized the relevance of the digital tools in the current design practice. In their opinion, these tools are particularly useful as a quick and effective means of generating alternatives, and as a flexible and effective mode of visualizing solutions, which is helpful in communicating the idea to the client.

[5] The calculation of the ranking mean is identical to the one employed in E1 (detailed in section **7.2.4**).

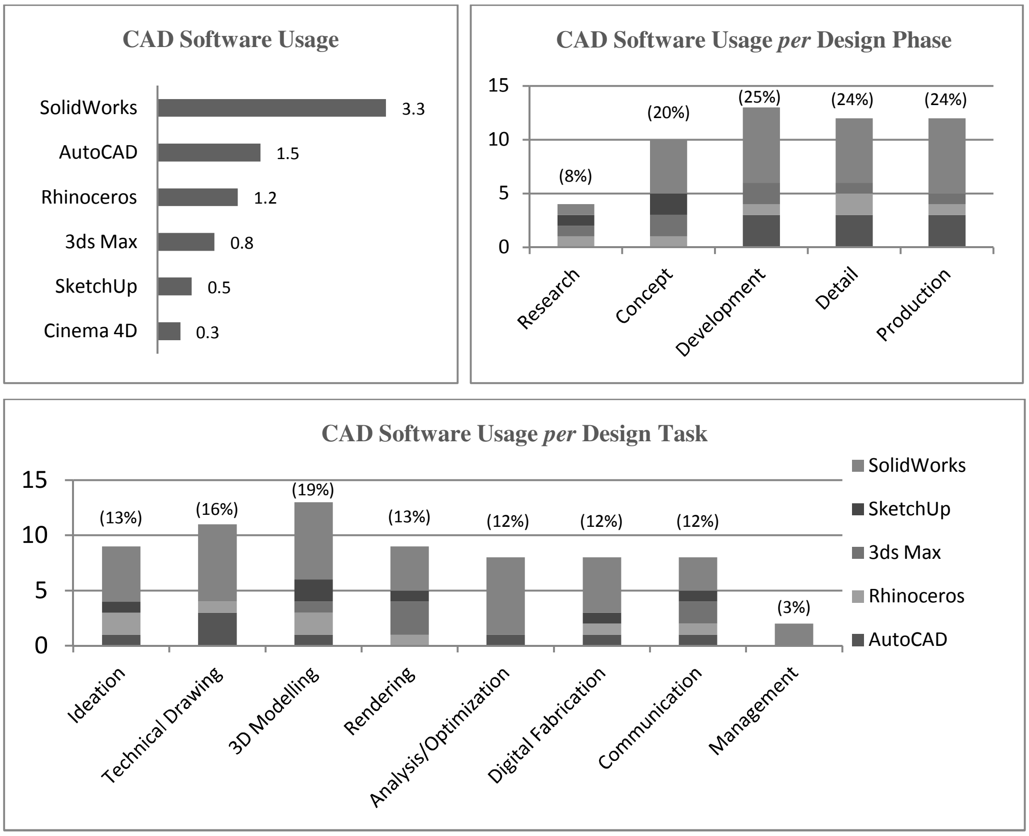


Fig. 7.12 Experience of E2 participants with CAD software

As mentioned earlier, all participants have recognized experience in chair design, having at least one awarded chair or a chair exposed in a design exhibition. Similarly to E1, the chair design experience of the participants was assessed according to the design phase achieved for each of the following contexts: industry, design studio, design competitions and academic projects. All participants achieved the production phase in one or more of the given contexts: 7 in industry (70%), 6 in design studios (60%), 4 in design competitions (40%), and one in academic projects (10%).

Participant's Design Process

In the pre-test interview, the participants were confronted with the analysis of the design process of one chair of their authorship. Note that the design process cannot be generalized, since it is inherent to a given designer and to a given project. The analysed chairs are depicted in **Fig. 7.13**. The goal of this procedure was to validate some of the ChairDNA features and to gather directions for future developments of the tool. Note that it is not ChairDNA's aim to mimic the designer's process, but it needs to be coherent with it in order to provide a relevant aid to the designer.

Fig. 7.13 Analysed chairs in E2 (image sources in **Appendix 7.B.6**)

The datasheets of the chairs analysed by the participants are available in **Appendix 7.B.6**. The sheets contain information regarding design (designers and design date), production (producers and production date), commercialization (seller and price), client, materials and manufacturing techniques, dimensions, sampling source and image source.

The products were at different development states at the time of the E2 study: detail (**P4** and **P7**), production (**P8**) commercialization (**P1, P3, P5, P9** and **P10**), and discontinued (**P2**, **P6**). The chairs reached different production volumes: 2-10 units (**P2, P5** and **P6**), 11-100 units (**P1**, **P3** and **P10**), and 101-100.000 units (**P9**). Most chairs (8; 80%) comprise options regarding colour, material or finishing, and four chairs (40%) belong to a design collection. This fact makes pertinent the use of ChairDNA for quick generation of design collections (although restricted to multipurpose chairs, stools and side tables).

The constraints of the design processes of the analysed chairs, imposed both by the design brief and the designer, are summarized in **Fig. 7.14**. The restrictions imposed by the design brief relate to more practical ones; mainly comprising materials (80%), sustainability (70%), cost (60%), and ergonomics (50%). On the contrary, the restrictions imposed by the designer are more formal and symbolic ones, related to function (50%), symbology (50%), and aesthetics (40%). It was verified that the designers' constraints are in accordance with their guiding principles (described in **Appendix 7.B.11**).

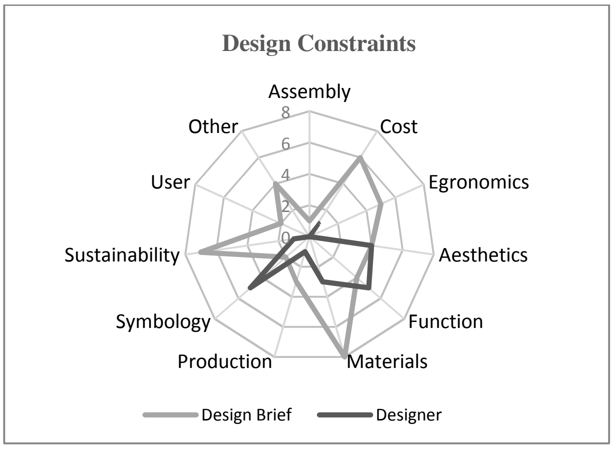
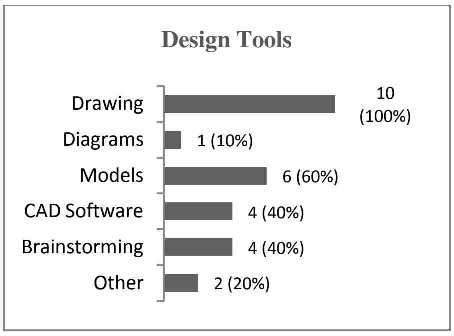


Fig. 7.14 Design constraints of the design process of the E2 analysed chairs

The information searched by the designers in the concept phase of the analysed chairs mainly addressed materials (70%), followed by ergonomics, function, production and symbology (30% each). The main gaps noticed by the participants in the available information regard the materials. ChairDNA 1.2 addresses few particular aspects of the design process: structure (related to function), shape (related to aesthetics), and anthropometrics (related to ergonomics). Based on the former considerations, further ChairDNA features should rely particularly on materials.

The design tools employed by the designers during the concept phase of the analysed chairs (**Fig. 7.15**, left) were: drawing (used by all), models (6; 60%), CAD software (4; 40%), brainstorming (4; 40%), and diagrams (1; 10%). The mostly used CAD software (**Fig. 7.15**, right) was SolidWorks (4, 40%) and Rhinoceros (2; 20%). SolidWorks is typically used for technical drawing, 3D modelling and rendering; while Rhinoceros is frequently used for ideation and 3D modelling tasks. Currently, ChairDNA can work with Rhinoceros but not with SolidWorks.



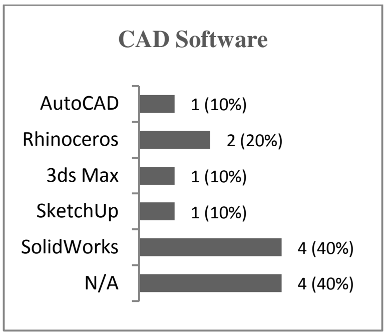


Fig. 7.15 Design tools of the design process of the E2 analysed chairs

The generation process of the form of the analysed chairs was mainly exploratory, but the analytical one was also employed. During the process, most designers generated several alternatives (and then selected one); only two generated one alternative (comprising several versions). The process described by some participants is quite similar to the ones supported by ChairDNA: the design **P5** was generated from a transformation process and **P8** from an additive process. However, **P4** resulted from a subdivision process (which is not included in ChairDNA). Two participants (designers of **P2** and **P10**) described their shaping process as a 'single gesture'

(**Fig. 7.16**, left), and those were the ones more uncomfortable with the generation process imposed by ChairDNA, which is fragmented into parts. Some designs were inspired by existing chairs (e.g. **P9** was influenced by **Gonçalo**), and others by design styles (e.g. **P6** was influenced by Jasper Morrison's style). One participant's design process (**P7**) is typically based on redesign, which made him enjoy the usage of ChairDNA templates:

> *"Truth be told, almost all chairs depart from certain types of iconic forms" (participant P7).*

The generation order of the analysed chair parts was, from first to last: Seat, Legs, Back, Arms, Stretchers and Base. The sequence is suitable to the one displayed by ChairDNA (which starts by either the Legs or the Seat) and is in accordance with the ones employed by the participants within ChairDNA (**Appendix 7.B.12**). However, some participants start the process by the chair Back (which is not allowed in ChairDNA). Two participants (20%) used guides to support the generation of the form of the chair (**Fig. 7.16**, right). These guides are very similar to the ones implemented in ChairDNA.

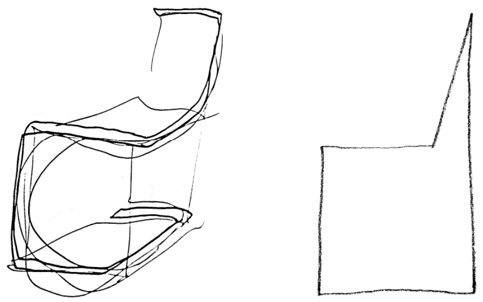


Fig. 7.16 Design drawn by a 'single gesture', from the participant P2 (left), and guides used in chair design, by the participant P10 (right)

The critical difficulties of the concept phase mentioned by the participants (**Fig. 7.17**) are mostly related to the selection and generation of alternatives (respectively, 40% and 20%) and time management (30%). ChairDNA is oriented to support the generation of alternatives, but in the future it could include mechanisms for the selection of alternatives, by providing analysis and optimization features. The tool can arguably contribute to a better time management, by allowing a quick generation and edition of designs.

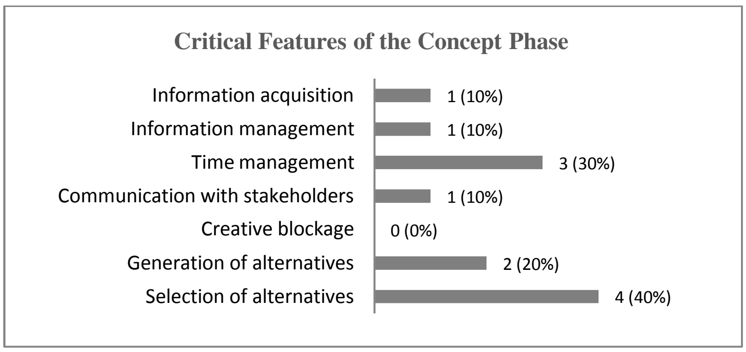


Fig. 7.17 Critical features of the concept phase of the E2 analysed chairs

7.3.5 Results and Discussion

The main results of E2 will be discussed along the following topics: (i) task outcomes, (ii) ChairDNA 1.2 usability, (iii) ChairDNA 1.2 usefulness, and (iv) recommendations for future versions.

Task outcomes

In E2, the participants were asked to accomplish four tasks. Each task resulted in a 3D digital model and a set of five usability metrics: (1) *time on task:* the time spent by the participant in each task[6]; (2) *completion rate:* the percentage of the subtasks accomplished by the participant (in relation to the total number of subtasks); (3) *error number*: the number of errors made by the participant in each task; (4) *help number*: the number of assistances provided by the moderator to the participant in each task; and (5) *ease of use*: the rate of the easiness on performing a task on a 1-5 scale (being 1 – very difficult and 5 – very easy), from the participants' perspective. The results of each task, in the format (Mean; Standard Deviation), are summarized below:

T1) *Free exploration of ChairDNA*: in this first task, the participants were invited to freely explore the program. The achieved design states and usability metrics are displayed in the **Appendix 7.B.7**. Some participants generated complete chair designs; others produced incomplete designs, while one merely resized the guides. This task was the second longest one (0:16:36; 0:06:22); but was easy to perform, according to the participants (3.8; 0.79). The completion rate was not calculated for this task, since there was no specific goal to accomplish. Few errors have been committed (0.5; 0.53); however many helps were provided in this first contact with ChairDNA 1.2 (7.9; 3.07).

T2) *Reproduction of a chair*: in this task, the participants had to reproduce, with the highest accuracy level allowed by ChairDNA 1.2, the chair **214**, shown in a figure (**Appendix 7.B.2**). **Fig. 7.18** illustrates the original chair and the correct solution (above), the resulting designs (middle) and usability metrics (below). This was the longest (0:19:57; 0:07:14) and the most difficult task (3.0; 0.71). The number of errors (4.56; 2.74) and helps (10.89; 5.69) was also the highest among all tasks. The difficulty of the task, from the participant's perspective, was justified by the complexity of the design, which made it hard to implement, and by the dissatisfaction with the low degree of accuracy allowed by ChairDNA 1.2. In this task, the completion rate was given by how similar the participant's solution was to the correct solution (70.6; 25.8). The solution that is more similar to the correct one is **P9** (91%), although its generation was the one that used the higher number of helps. The participant P7 did not accomplish this task.

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[6] The time on task of the participant P1 was not recorded, due to software problems.

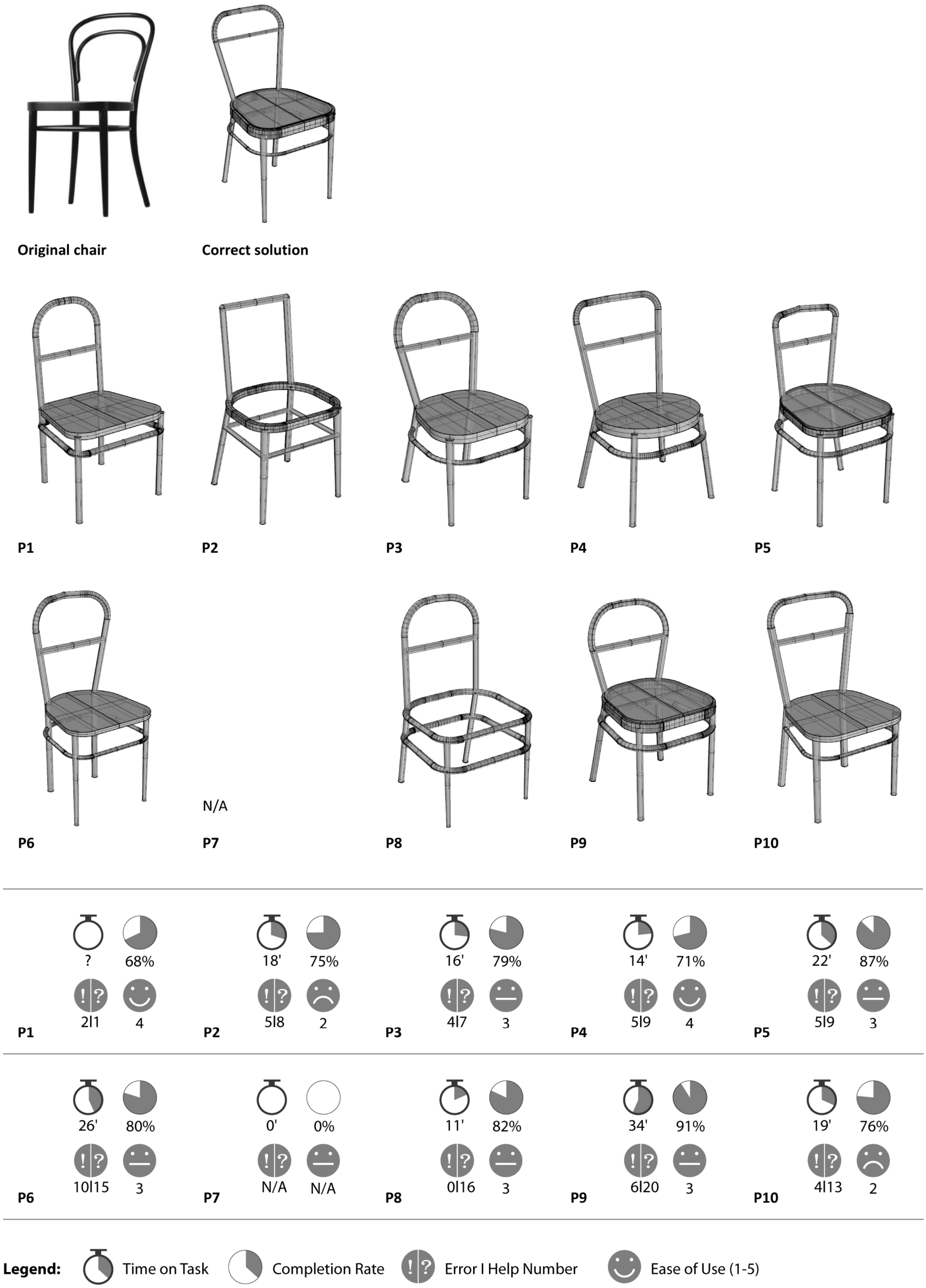

Fig. 7.18 Task 2 of E2: correct solution (above), resulting designs (middle) and usability metrics (below)

T3) *Transformation of a chair*: in this task, the participants had to open an existing chair of the ChairDNA 1.2 template library (the **Gonçalo** chair) and make five short modifications enumerated by the moderator: (1) change the number of legs to three; (2) add a Seat Front Rail; (3) add four Seat Cross Rails; (4) remove the armrest; and (5) place a base with a radial shape. The original chair and the correct solution are displayed in **Fig. 7.19** (above). The resulting designs of Task 3 (which are almost all alike the correct solution) are illustrated in **Appendix 7.B.7** and the respective usability metrics are presented in **Fig. 7.19** (below). This was the fastest (0:03:47/0:00:42) and easiest task (4.3; 0.67), and the completion was almost perfect (98.8; 4.0). The error number (0.7; 1.06) and help number (2.2; 1.69) was considerably low.

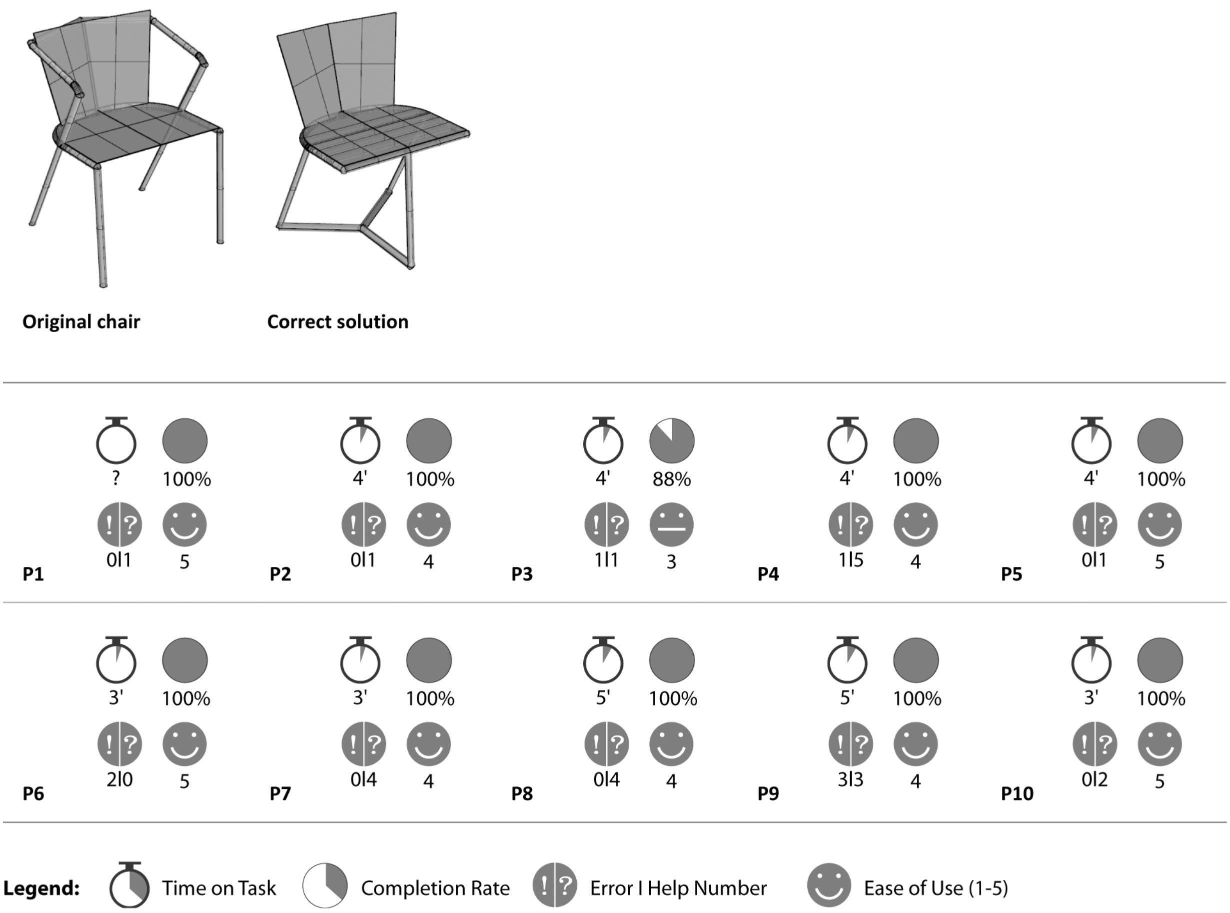

Fig. 7.19 Task 3 of E2: correct solution (above) and usability metrics (below)

T4) *Design of a chair*: in this last task, the participants had to design an original multipurpose chair with the aid of ChairDNA 1.2. Participants could use the aforementioned analysed chairs as an inspiration, and could also start from a template or a random design. The resulting designs and usability metrics of Task 4 are displayed in **Fig. 7.20**. The participants took a relatively short time to accomplish the task (0:13:11; 0:07:41), but considered this task as the most difficult after Task 2 (3.4; 1.07). Still, most of them completed the goals defined for this task (95.0; 10.5). The participants did not commit many errors (0.6; 0.70) but benefited from some helps (5.5; 3.10).

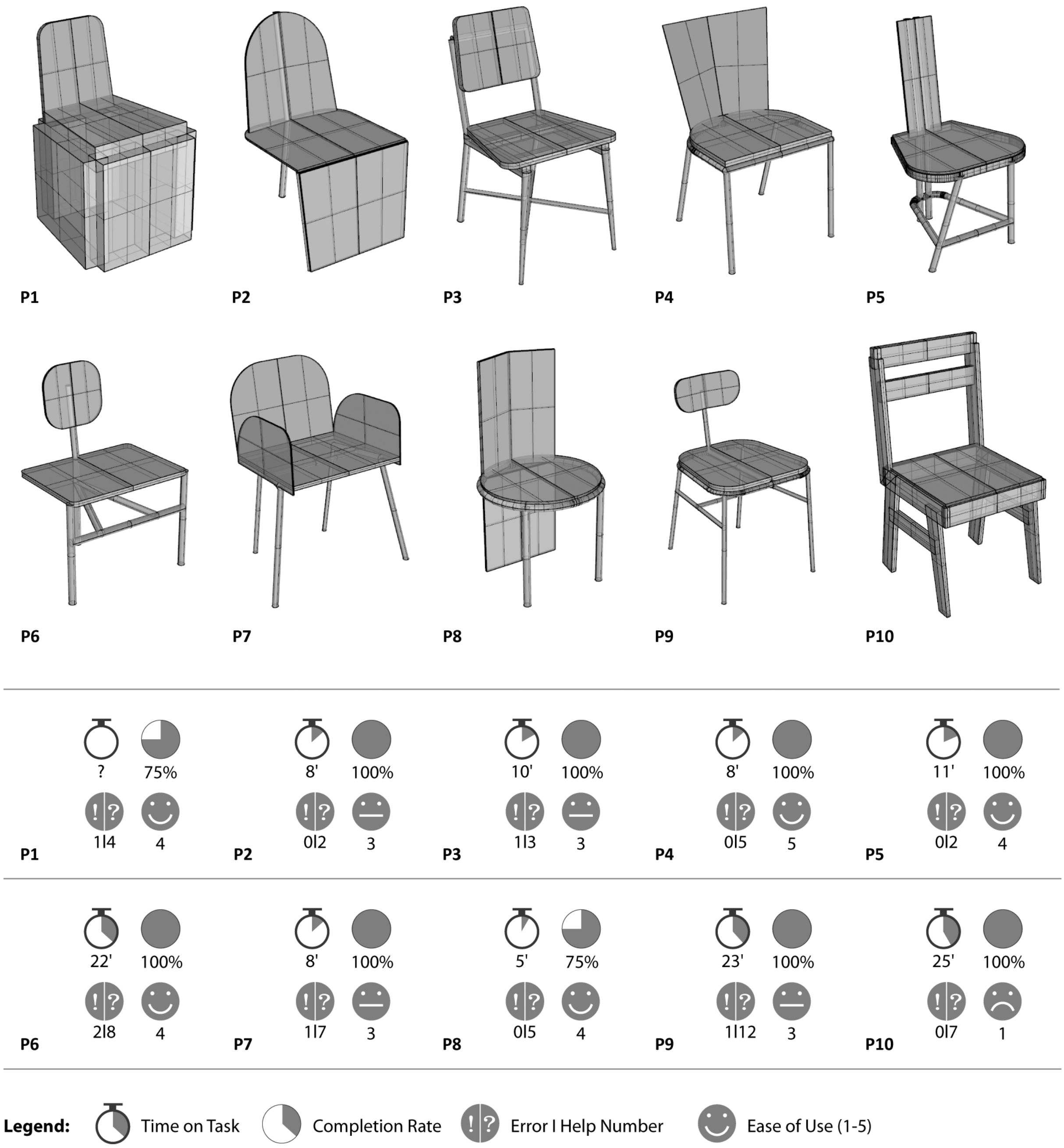

Fig. 7.20 Task 4 of E2: resulting designs (above) and usability metrics (below)

The resulting designs and respective usability metrics of the pilot test are displayed in **Appendix 7.B.7**. The procedures for the calculation of the completion rate (of Tasks 2, 3 and 4) are included in **Appendix 7.B.8**.

The participants were asked to describe in detail the design process of Task 4. Different strategies were employed in the generation process (**Fig. 7.21**, left): one participant (**P1**) intended to reproduce the CUT chair of his authorship (illustrated in **Fig. 7.13**), three participants (**P2**, **P4**, **P7**) redesigned chairs available in the ChairDNA template library; two participants developed a pre-existing idea (a classroom chair in the case of **P9** and a wooden board do-it-yourself chair in the case of **P10**); and four (**P3**, **P5**, **P6**, **P8**) designed a chair by freely exploration of ChairDNA 1.2. The inspirations of the participants are displayed in **Appendix 7.B.9** and are summarized in **Fig. 7.21** (right): five participants were inspired in an existing chair (50%), three in a particular chair type (30%), and two participants did not mention any inspiration (20%). The participants classified the form generation process as being mostly exploratory.

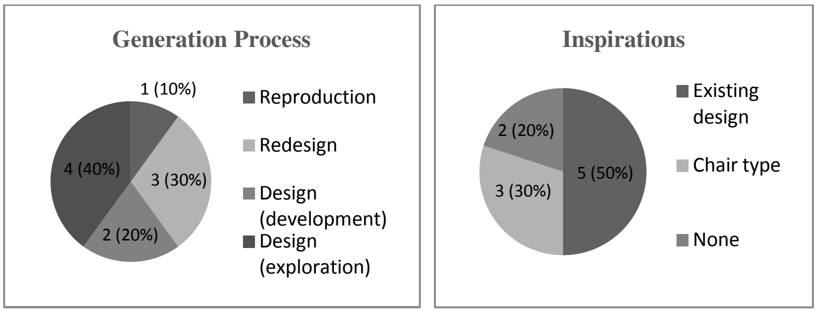

Fig. 7.21 Main results of the design process used in the Task 4 of E2

Almost all the participants did not use any tool beyond ChairDNA 1.2, probably because they did not have much time available to complete the task. Only one participant (**P9**) used drawing before using ChairDNA, to sketch the concept (illustrated in **Appendix 7.B.9**). Moreover, none of the participants edited the 3D digital model after using ChairDNA.

Concerning the envisioned materials for the final solution (**Fig. 7.22**, left), the preferred ones were metal for the frame and wood for the seat and back panels. Two participants employed a different material in the back in relation to the seat, and one participant (**P7**) did not indicate any material. Half of the participants considered the materials as a constraint of the form generation process (**Fig. 7.22**, right).

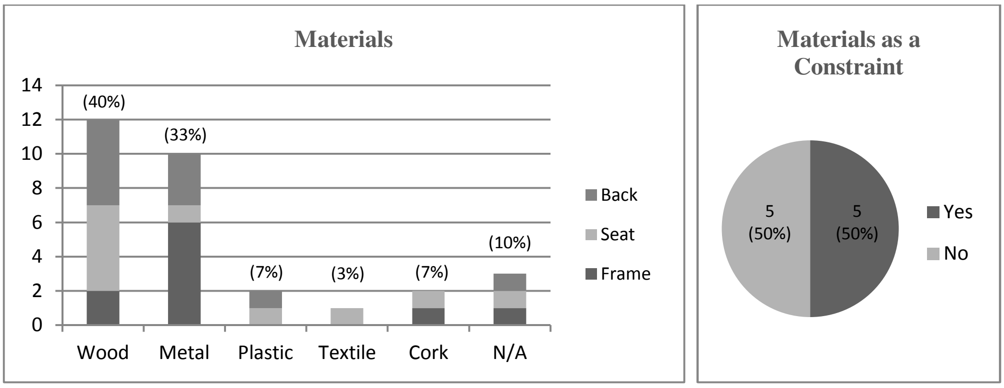

Fig. 7.22 Envisioned materials for the resulting designs of Task 4 of E2

ChairDNA Usability

The evaluation of the ChairDNA 1.2 usability and usefulness was mostly done through five-point Likert scale questions (from ‘strongly disagree’ to ‘strongly agree’). The results of this and the next section are presented in the format (Mean; Standard Deviation).

Overall, the ChairDNA 1.2 usability was positively evaluated (**Fig. 7.23**, left). The program was considered easy to learn (4.1; 0.74), easy to use (3.7; 0.48), and coherent as a whole (4.0; 0.47). Participants found that the use experience was satisfactory (3.7; 0.82), but they did not approve the efficiency of ChairDNA in terms of performance (2.9; 1.29). Indeed, the ChairDNA 1.2 efficiency becomes lower as parts are being added. Lastly, participants did not find the program flexible in adapting to their needs (2.9; 1.29).

The ChairDNA 1.2 commands were also positively rated (**Fig. 7.23**, right), considering aspects such as the activation sequence (4.0; 0.82); the quantity of available commands (3.0; 0.82); the distribution among the windows (3.5; 0.71); and their terminology (3.7; 0.95). Participants did not consider the available commands sufficient.

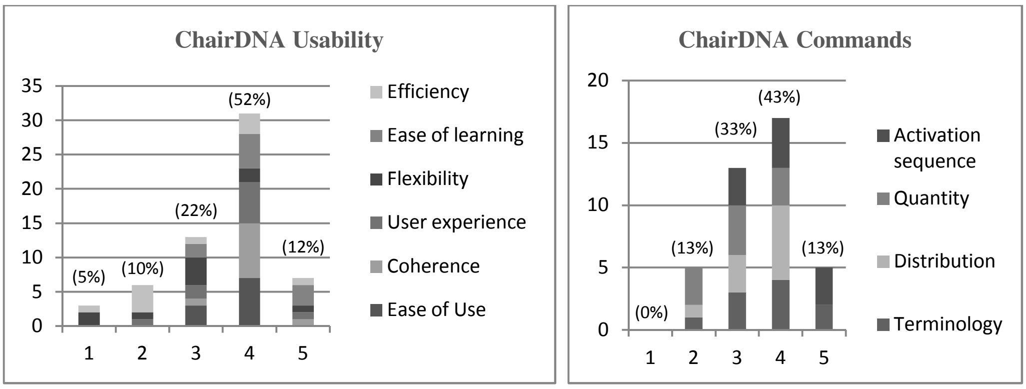

Fig. 7.23 ChairDNA 1.2 usability results

The inclusion of icons along with the commands’ names was strongly recommended (4.5; 0.71). The name of the program was considered adequate (4.6; 0.70); one participant (P9) referred that the same underlying template can be materialized in different forms, analogously to what occurs in the genetic code.

ChairDNA Usefulness

The ChairDNA 1.2 usefulness as a design tool was evaluated by the participants as being slightly positive (**Fig. 7.24**). Although the tool limits decision-making (3.5; 1.08), which, as mentioned by one participant, can be advantageous or disadvantageous, it also allows the emergence of unexpected solutions (3.2; 1.03). Participants were not satisfied with the accomplished solution (2.9; 0.88), mainly due to limitations on shape detail (e.g. lack of curves) and on the alignment of the parts. They considered the generation logic of the tool to be adequate to the concept phase of the chair design process (3.4; 1.17); however, they did not consider that the tool provided them with new knowledge regarding the chair shape and structure (2.1; 0.99). The tool was considered a useful aid to the concept phase of chair design (3.7; 0.95), and the participants would like to use the tool in future design projects (3.7; 1.06).

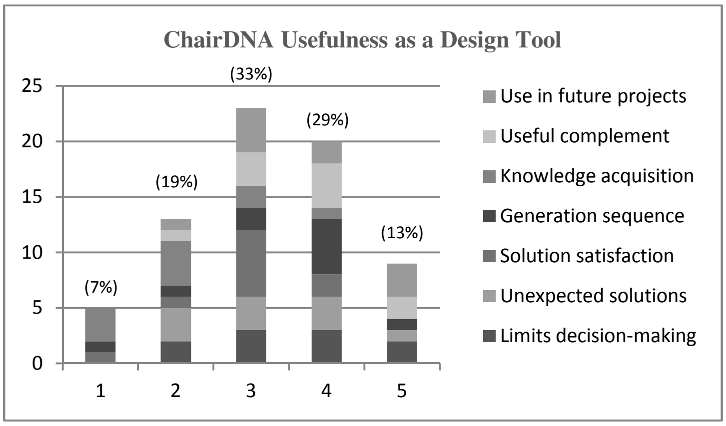

Fig. 7.24 ChairDNA 1.2 usefulness results

Participants are not sure whether they would like to purchase ChairDNA 1.2 (3.1; 1.10), mostly because the program is restricted to one particular type of product (multipurpose chairs). However, they would recommend ChairDNA to other designers (3.8; 0.79). The overall satisfaction with ChairDNA 1.2 was positive (3.6; 0.70).

Participants did not agree on the usefulness of using templates (3.5; 1.43) and random designs (2.8; 1.40). In their opinion, templates, on the one hand, are not useful if the user already has a concrete idea to be developed, but on the other hand are suitable for redesign (of the iconic chairs available in the program library). Random designs, despite generating bizarre results and not allowing the user to control the generation process, may give the user inspiration for new ideas and thus help overcoming creative blocks:

"[The random mode] is the computer being creative" (participant PP)

The ChairDNA tool is intended for the concept phase of the design process. Participants confirmed the pertinence of the application in this phase (6; 38%), but also highlighted its applicability to the research phase (5; 31%), allowing to study several options for the shape and structure of the chair. The usage of the tool in the development phase was also considered suitable

(3; 19%), being ChairDNA compared to font editing tools. The participants hardly approved ChairDNA for the detail and production phases (1; 6% each). Besides the applicability of ChairDNA to design tasks, participants also enhanced its potential for pedagogical purposes (e.g., to teach anthropometrics, chair types, and relations between parts) and industrial applications (since designs can be easily adapted to specific production requirements).

Participants indicated a set of strengths and weaknesses of ChairDNA 1.2. On the strengths side, they emphasized the advantage of having a real-time and full-scale visualization of the design during the generation process, although one mentioned the danger of considering the ChairDNA output an end product. Participants also highlighted the ability of the tool to quickly generate designs as an effective means of exploring alternatives. The parameterization of the chair parts and its adequacy to anthropometric standards were also appreciated. Moreover, the use of templates was considered useful for redesign, and some participants enjoyed the random command as a creative unlocker. The capacity of the tool of generating 'impossible' solutions was considered an aid for creativity. One participant mentioned that ChairDNA can be used by inexperienced CAD users, which was verified in this experience; from the two participants without experience in 3D CAD software, one of them had a harder time in using ChairDNA, but the other quickly learned how to use it, as demonstrated by the quote below:

> *"ChairDNA is playful, because one gets enthusiastic about what one is doing, and becomes surprised by his/her own abilities" (participant P8)*

On the weaknesses side, the participants would like to have more shape detail, although one mentioned that the current level of detail is excessive for the concept phase, and other would like to have two levels of shape detail in the same tool. Some participants considered the limitation of the tool to a single type of chair a significant shortcoming. Other users experienced difficulties derived from their inexperience with ChairDNA in particular and 3D CAD software in general. Two participants considered the fact that ChairDNA was constructed upon existing chairs a limitation to creativity. Others defended that ChairDNA is supporting a task in which the designers are already good; it should instead automate routine design tasks that would benefit in terms of speed. Moreover, many participants argued that the ChairDNA tool lacks the intuitiveness side of freehand drawing, since it does not allow a direct interaction in the shape and the generation process is fragmented into chair parts:

> *"ChairDNA does not have the spontaneous, inaccurate, manual side of drawing" (participant P7)*

ChairDNA Recommendations

Before having any contact with ChairDNA, the participants were asked about what features they would like to include in a digital tool for the generation of the form of the chair. They mentioned features which are already supported by ChairDNA, such as anthropometric ranges and the quick visualization of the design being generated. The most desired feature not included in ChairDNA is structural and shape analysis, which comprise for instance the calculation of weight, maximum stacking units (for stacking chairs), and joint tests. Other mentioned features include: easy transposition to digital fabrication (for instance to CNC machines); visualization of the design in virtual/augmented reality; and approximation of the 3D digital modelling to the hand gesture of sketching (using for instance the approaches of 3D digital drawing or computer-aided perspective drawing[7]).

After using ChairDNA 1.2, participants were questioned about other features they would like to see included in the tool. They recommended the addition of further shape detail (such as curves and joints), and the introduction of materials and analysis components, including structural analysis and motion simulations (e.g. for folding chairs). Participants would also like to extend the language of designs beyond multipurpose chairs, in order to include stools, office chairs, easy chairs, children's chairs, and lounge chairs. Note that ChairDNA can already generate stools, but only one participant mentioned the fact. It was also encouraged the addition of asymmetric chairs and other types of furniture (beyond seats). Lastly, participants also recommended to make a more user-friendly interface, and to allow the user to manipulate directly in the 3D shape.

E2 resulted in a list of 51 recommendations, which can be consulted in the appendixes of the previous chapter (**The ChairDNA Design Tool**). Participants detected 14 bugs, suggested the edition of 12 features and the inclusion of 25 new features. The most desired features are related to the interface (direct manipulation in the 3D model, inclusion of icons, and replacement of percentage units by absolute units), to the alignment of parts, and to the inclusion of templates for predefined types of chairs (e.g. low back chair and stacking chairs). Besides the participants recommendations, the list also includes 20 recommendations detected by the developer of the ChairDNA tool (7 bugs, 4 editions and 9 additions) and 3 extra recommendations of E1 that were not implemented in ChairDNA 1.2 (comprising the addition of 3 features). In short, the participants of both evaluations detected 73% of usability issues, which is under the 82% predicted by Macefield (2009).

The totality of the results of E2, which were summarized in this section, can be consulted in: **Appendix 7.B.10** (observation notes), **Appendix 7.B.11** (interview statistics), **Appendix 7.B.12** (user test statistics) and **Appendix 7.B.13** (questionnaire statistics).

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[7] The 3D digital drawing consists in 'sketching' in 3D space, being the gesture of the hand automatically transposed to a 3D digital model; this process is used in a studio Front project called *Sketch Furniture* (http://www.frontdesign.se/sketch-furniture-performance-design-project). Computer-aided perspective drawing is the automatic translation of a hand-made 2D perspective drawing into a 3D digital model; this topic is being researched in MIT (http://architecture.mit.edu/computation/lecture/computer-aided-perspective-drawing).

7.4 Conclusion

This chapter described a user evaluation of ChairDNA (described in the chapter **The ChairDNA Design Tool**), which comprised the sixth and last stage of the computational model presented in the **Introduction** chapter. Two independent evaluations were made to each of the two main versions of ChairDNA: in a first evaluation (E1), ChairDNA 1.1 was tested by 19 Portuguese design students, and in a second evaluation (E2), ChairDNA 1.2 was tested by 10 Portuguese design practitioners. Although the tests comprised significant differences among them and E1 had almost twice the participants of E2, a comparison will be provided in the following lines, regarding goals, methods, participants and results.

The main goal in both evaluations was to assess the ChairDNA usability and usefulness as a tool for the concept phase of chair design. Moreover, both evaluations were intended for diagnosis and improvement of subsequent product versions.

The evaluations employed slightly different methods. Both occurred at the participant's workplace, but E1 comprised group moderated sessions, while E2 included individual moderated sessions. E1 and E2 employed questionnaires, interviews and observation testing methods, and encompassed screen recording methods. The main task proposed to the participants was to design a multipurpose chair. All the participants experienced ChairDNA, but its use to develop the design was optional in E1 and mandatory in E2. Both evaluations contemplated a preparatory task of freely exploring ChairDNA, while E2 also comprised two extra introductory tasks (to reproduce a chair and to edit a chair). All the resulting designs were delivered in the format of a 3D digital model.

Both evaluation methods comprised some shortcomings: in E1, the lack of individual sessions and the few screen records compromised the achievement of usability metrics; moreover, the questionnaire was not answered by all the participants. E2 overcame some of those issues, but the reproduction task was the most difficult and time-consuming one, which was not desirable in the light of the evaluation goals. Moreover, the participants did not have time to mature the project (unlike the students in E1), as there was only a single session for each.

In E1, the majority of the participants were females aged 20-33, while E2 comprised mostly males aged 26-56. The participant's expertise was assessed in terms of CAD software; these tools were usually employed by E1 students in the later phases of the design process, while E2 practitioners typically used them across every design phases. However, two E2 participants did not have experience in 3D digital modelling. The participant's experience in chair design was also evaluated; E2 participants had significantly more experience in this domain than E1 participants, since they were selected based on awarded chair designs of their authorship.

The results in both evaluations were discussed on the following topics: task outcomes (resulting designs and design process), ChairDNA usability and usefulness, and recommendations for subsequent ChairDNA versions. The E1 task resulted in 19 designs, although 3 were not generated with ChairDNA. Only 3 designs were exclusively generated with ChairDNA 1.1, since the remaining was later edited in 3D CAD software. The E2 design task resulted in 10 designs, all exclusively generated in ChairDNA 1.2. In both evaluations, the resulting designs contemplate a varied number of chair types and, in the case of E1, even some unexpected solutions for the developer.

In both evaluations, the participants could depart from a previously formalized concept, moreover, in the case of E2, participants could also start from a template or a random design. The majority of the E1 participants did not reproduce the initial idea; they mostly employed redesign and design processes motivated by the exploration of the solution space within ChairDNA. The majority of the E2 participants designed a chair from scratch, but some also redesigned existing templates and one tried to reproduce a design. E2 participants did not use other tools beyond ChairDNA nor made adjustments in the 3D model, unlike E1 participants. However, they considered the material as a constraint more frequently than students. The preferred materials envisioned for the final solutions were, in both cases, metal for the frame and wood for the seat and back panels.

Overall, the participants of both E1 and E2 positively evaluated the ChairDNA usability and usefulness as a chair design tool; although E2 practitioners gave lower scores than E1 students. All participants found ChairDNA easy to use and to learn, but they poorly evaluated the program's efficiency and flexibility. Both E1 and E2 participants found ChairDNA useful, although they were not very satisfied about the achieved solution, as they were expecting more shape detail. They considered that the program limits decision-making but is also capable of generating unexpected solutions.

Participants also assessed some ChairDNA advantages and disadvantages. (i) Regarding advantages, ChairDNA is a quick and effective means of generating designs, adequate to the anthropometric standards; allows a quick and accurate visualization of the design during the generation process; can easily transform existing designs; can be an aid for creativity, since it can generate unexpected and impossible solutions; and is easy to use, since it requires little training and knowledge in chair design and 3D digital modelling. (ii) Considering disadvantages, ChairDNA has a slow performance; has a low level of shape detail and, although it can generate many types of multipurpose chairs, it is limited that particular chair type. Moreover, the designers considered that ChairDNA is supporting a task where the designers are already good at and it does not encompass the spontaneous side of freehand drawing (since the generation is fragmented into parts and it is not made by a direct interaction in the shape).

E2 also comprised the analysis of the participant's chair design process, regarding the case of one design of their authorship. Many characteristics of their process are suitable to the ones supported by ChairDNA, while others are not: (i) many chairs are part of a design collection, which makes pertinent the use of ChairDNA for quickly transforming designs; (ii) the design constraints imposed by the design brief were more practical, while the ones imposed by the designer were more functional, formal and symbolic; ChairDNA currently only addresses the functional and formal ones; (iii) the designer's process, mostly exploratory and comprising the generation of several alternatives, was also used by the participants with ChairDNA; (iv) ChairDNA supports additive and transformation processes, but not the continuous fluid process inherent to freehand drawing; (v) the design process is commonly influenced by other chairs and/or styles, which is a feature addressed by ChairDNA; (vi) the generation sequence employed by the designers (starting by the Legs or the Seat) matches the one presented by ChairDNA, but some users also start by the Back, which is not allowed in ChairDNA; (vii) some participants use similar guides to the ones of ChairDNA; (viii) the critical features of the concept phase are mostly related to the generation and selection of alternatives; ChairDNA can aid the designer with the former but not with the latter feature.

Both evaluations resulted in a recommendations list. Many recommendations of E1 were included in ChairDNA 1.2, such as the inclusion of a save command and the edition of the slider values through numerical input. Participants of both E1 and E2 suggested the inclusion of more shape detail (such as curves and joints) and more types of seating furniture. The participants of E2 showed more interest in including materials and structural analysis than E1 participants, and also suggested a more intuitive interaction (directly in the 3D shape).

Future work could comprise tests with other users, evaluating different applications of ChairDNA. In this chapter, ChairDNA was evaluated as a pedagogical tool and a design tool; further tests could be conducted with more advanced design students and design practitioners of different nationalities. Moreover, ChairDNA could also be evaluated as a fabrication tool (comprising tests with manufacturers), as a customization tool (comprising tests with end users) and as an analysis tool (comprising tests with design historians).

Other evaluation methods could be employed, such as a workshop addressing a design competition, which would introduce a participant’s incentive (the competition prize), a realistic briefing, and the evaluation of the solution by experts beyond the participants (the competition jury). It would be suitable to include a task to generate a design collection (e.g. stool, side chair and armchair). Another approach could include comparisons between two groups of participants: (i) one designing with ChairDNA *versus* other designing without ChairDNA, or (ii) one designing with ChairDNA *versus* other designing with the Multipurpose Chair Grammar.

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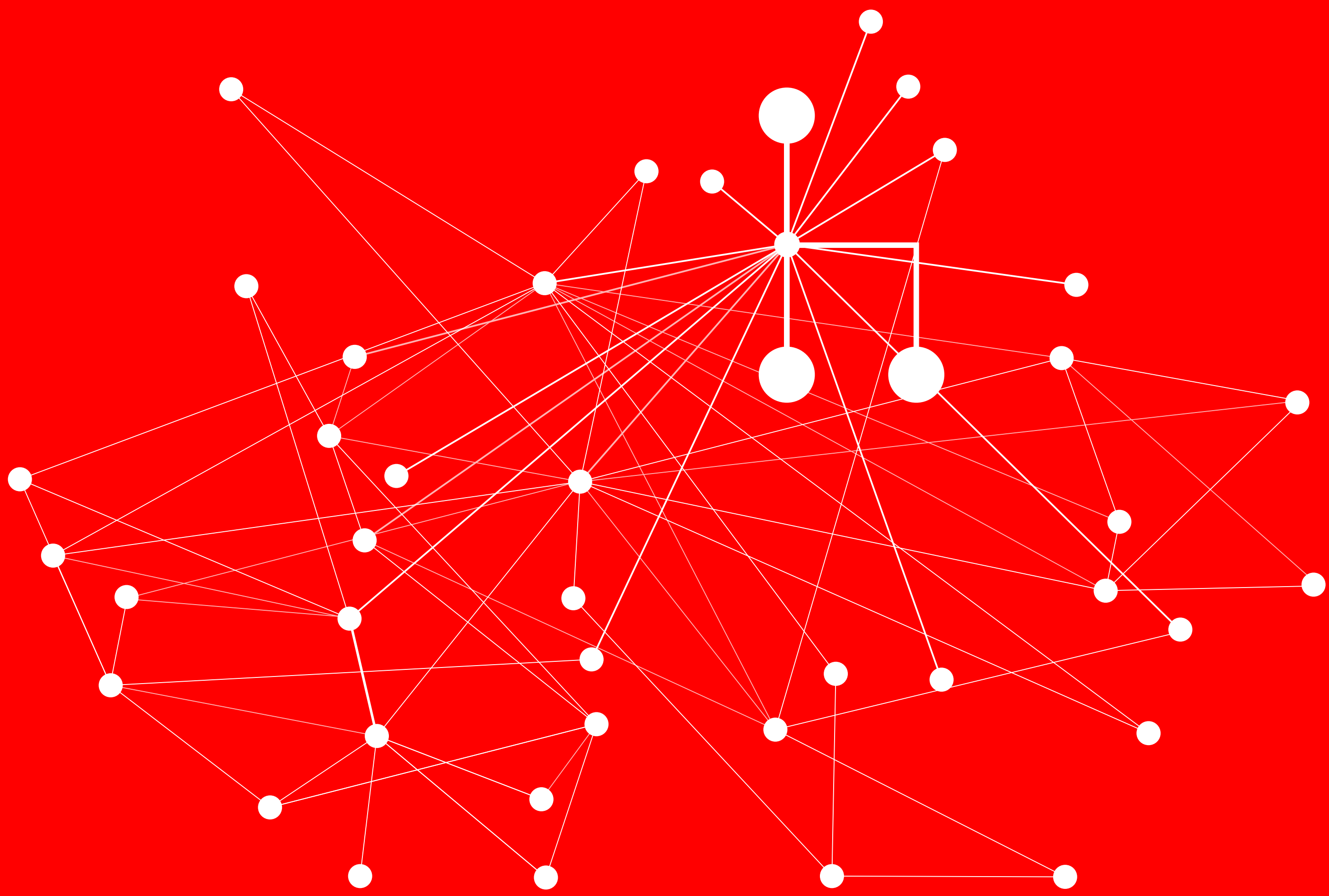
7.6 Appendixes



Conclusion

8

8 CONCLUSION

This chapter provides an overview of the research and summarizes the research findings, divided into main findings (addressing the hypothesis and research questions), and secondary findings. Moreover, the main and secondary contributions of the research are clarified and, lastly, a set of recommendations for future work is detailed.

8.1 Research Summary

This research thesis described a computational model whose goal was twofold: (i) to generate a large variety of designs within a product class and (ii) to provide a useful tool for the design concept phase.

The background of this model relies on studies of form based upon computational and ontological approaches. These studies allow capturing the diversity inherent to the individuals of one class, by the description of the similar characteristics that all individuals share and the dissimilar characteristics that make each individual unique. This reasoning can be applied to product classes and lead to practical applications, such as computational design tools that describe and generate of a large variety of designs within a given domain.

The development of the computational model followed a cyclic process, comprising six main stages: *plan*, *sample*, *ontology*, *grammar*, *implementation* and *evaluation*. This model was applied to the product class of multipurpose chairs, as a case study. The stages comprised the following tasks:

Stage 1) **Plan**: definition of the product class, goals and requirements of the computational model;

Stage 2) **Multipurpose Chair Sample**: selection and description of a sample of designs (46 multipurpose chairs and 1 stool) representative of the product class;

Stage 3) **Multipurpose Chair Ontology**: development of an ontological classification of the selected product class, based on literature review and on the analysis of the sample described in stage 2;

Stage 4) **Multipurpose Chair Grammar**: development of a parametric set grammar, based on the ontology described in stage 3, and capable of describing and generating designs of the sample referred in stage 2 and original multipurpose chair designs;

Stage 5) **The ChairDNA Design Tool**: translation of the grammar described in stage 4 to a digital environment, and test of its generative capabilities;

Stage 6) **User Evaluation of ChairDNA**: evaluation of the tool described in stage 5 by its target users: design students (in a first evaluation) and design practitioners (in a second evaluation). The evaluation followed a task-oriented approach, being the main task the design of a multipurpose chair using ChairDNA.

Each stage (except the plan stage) is described in one chapter of the thesis. These stages were revisited in four main versions of the computational model, with the exception of the *implementation* and *evaluation* stages, which were not addressed in the first two versions. The versions are defined by the product subclass considered at the plan stage:

Version 0.1) **Daciano Chairs**: multipurpose wooden frame chairs of the Portuguese designer Daciano da Costa;

Version 0.2) **Daciano-Jasper Chairs**: multipurpose wooden frame chairs of two designers: the aforementioned and the English designer Jasper Morrison;

Version 1.1) **Iconic Chairs**: multipurpose iconic chairs, including wooden chairs manufactured by the German company Thonet GmbH;

Version 1.2) **Multipurpose Chairs**: multipurpose chairs, including all the ones mentioned in the former versions.

The ultimate outcome of this research is translated into a grammar-based tool for the concept phase of multipurpose chair design. The tool describes the diversity inherent to the product class of multipurpose chairs, while embracing the similar characteristics shared by the designs of the class (i.e., seat and back parts with certain anthropometric dimensions). With the tool, the designer can generate and edit designs quickly and accurately, by manipulating chair parts and editing shape parameters. The 3D digital model of the design being generated is visualized in a CAD application.

Currently available computational design tools encompass two identified shortcomings: (i) the solution space is often restricted to a particular design style or design family, and (ii) their practical application is sparse, particularly in the concept phase, since they are typically used for proof of concept and are evaluated merely by the tool developers and students. With this in mind, the contribution of the computational model described in this research is twofold: (i) to contemplate a solution space addressing a large variety of types inherent to one product class; and (ii) to evaluate the practical applicability of the model as a tool for the concept phase of the design practice, comprising tests with design students and design practitioners.

8.2 Research Findings

This section discusses the research findings, divided into two categories: (i) main findings, which address the hypothesis and the main and secondary research questions (described in the **Introduction** chapter), and (ii) secondary findings.

8.2.1 Main Findings

Hypothesis

> *A computational model capable of generating a large variety of multipurpose chair types is a useful tool in the concept phase of chair design.*

This research comprised the development of a computational model. In order to verify the hypothesis, such model should present two major abilities: (1) to generate a large variety of multipurpose chair types; and (2) to be a useful aid in the concept phase of chair design. The demonstration of each of these two findings is described below.

The computational model is able to generate a wide range of multipurpose chair types.

The version 1.1 of the computational model was developed with the goal of describing and generating a large diversity of chair types. For that purpose, the selection of the corpus (detailed in the chapter **Multipurpose Chair Sample**) comprised chairs representing 30 different types of multipurpose chairs. The generative capabilities of the computational model can both be demonstrated by the ChairDNA tool and the Multipurpose Chair Grammar (MCG).

In the chapter **The ChairDNA Design Tool**, 102 designs (95 multipurpose chairs, 4 stools, and 3 tables) generated in ChairDNA are illustrated. ChairDNA is able to describe and generate designs from the corpus (upon which the system was developed), existing designs (which are not part of the corpus but belong to the language) and new original designs. The corpus designs and the existing designs (detailed in the chapter **Multipurpose Chair Sample**) comprise 70 different types of multipurpose chairs. The new designs generated in ChairDNA include 30 new types of multipurpose chairs (that were not contemplated by any chair of the sample but were described in the **Multipurpose Chair Ontology**). Therefore, ChairDNA is able to generate 100 different types of multipurpose chairs. The main chair types include one- to four-legged chairs, different seat shapes (round, square or trapezoid), several inner back frame configurations (with horizontal or/and vertical elements, no elements or one solid element), several stretchers and base configurations (e.g. H-, U-, and X-shaped) and arm and armless chairs.

The MCG is also capable of describing and generating corpus designs, existing designs and new designs. However, the generative capabilities of the MCG are slightly different from the ones of ChairDNA. On the one hand, the MCG cannot currently generate other designs beyond multipurpose chairs (e.g. stools and tables), but on the other hand, it can generate repeated chair parts, and thus it is able to generate a few more chair types.

The computational model is a useful tool in the concept phase of chair design.

The computational model was designed with the purpose of being used as a tool for the concept phase of chair design. The ChairDNA design tool was evaluated by 19 design students and 10 design practitioners. The details of the evaluation are available in the chapter **User Evaluation of ChairDNA**. The overall opinion of both design students and design practitioners was that ChairDNA was useful as a design tool for the concept phase, and was easy to use. However, the opinions were not consensual and the participants highlighted both strengths and weaknesses of the tool.

On the positive side, the users found that the tool provides a fast and accurate means for generating designs, adequate to anthropometric standards; provides a precise visualization of the design being generated; can easily transform existing designs; and can suggest unexpected solutions. Moreover, the participants found the tool easy to use, since it does not require experience in chair design nor in 3D digital modelling.

On the negative side, the users found that the tool lacked shape detail and, although it can generate many multipurpose chair types (as aforementioned), the fact that it cannot generate other types of chairs, seats or furniture items was regarded as a shortcoming. The designers considered that ChairDNA lacked intuitiveness and flexibility when compared to freehand drawing, mostly because the interaction is not made directly on the shape but on interface elements representing fragmented chair parts. In general, the designers gave a lower appreciation of the ChairDNA usefulness than the students, which may be derived from their higher experience in chair design.

Main Research Question

> *Is a computational model, capable of describing and generating a large set of multipurpose chair types, a useful tool in the concept phase of the design process?*

The answer to this main research question was already provided in the former section, within the hypothesis verification.

Second Research Question

> *What methodology would be effective in the development of a model that allows a systematic description and generation of a large variety of designs within a product class?*

This research presented a computational model, which is able to describe and generate a large variety of designs. The descriptive and generative system comprises three main representations (ontology, grammar, and implementation), all capable of describing and generating existing designs (selected in a sample) and new designs. The system only addresses the structure (functional parts) and shape of the designs. The computational model was developed upon a methodology comprising the following six stages (as detailed in the **Introduction** chapter):

Stage 1) *Plan*: selection of a product class, and definition of the goals and requirements of the computational model;

Stage 2) *Sample*: selection and description of a set of designs representative of the selected product class, including corpus designs (representing the main design types described in the ontology) and existing designs;

Stage 3) *Ontology*: development of an ontology-based system, able to describe the designs of the corpus (included in the sample). The system should describe the product's functional parts (i.e., the decomposition into mandatory parts – existing in all designs, and optional parts – existing in some designs), the definition of the main types of parts, the delineation of the main shape parameters, and the generation sequence of the parts;

Stage 4) *Grammar*: development of a grammar-based system, based on the former ontology. The system should be able to describe and generate corpus designs and other existing designs (included in the sample), and new designs within the selected product class;

Stage 5) *Implementation*: implementation of the former grammar-based system in a digital environment. The implementation should be able to describe and generate the same types of designs mentioned in the previous stage;

Stage 6) *Evaluation*: evaluation of the usability and usefulness of the implementation by the target users.

These six methodology stages can be revisited in repeated cycles, in increasing levels of complexity and detail. This methodology was proven to be successful when applied to the case study of multipurpose chairs. The same approach can be employed to the development of computational systems capable of describing and generating designs within other product classes.

Third Research Question

> *What degree of completeness can be achieved with a computational model that intends to reproduce as many types of chairs as possible?*

The computational model was tested in order to assess its completeness level. In the chapter **The ChairDNA Design Tool**, the generative capabilities of ChairDNA were evaluated according to three tests, which assessed whether the system was able to generate: (i) designs from the corpus (*descriptive test*); (ii) existing designs (*analytic test*), and (iii) new designs (*synthetic test*). Moreover, *a completeness test* was applied to the first two tests, to assess to what extent the system was able to generate existing designs, on a given shape abstraction level.

The results of the tests demonstrated that the system was able to generate (i) 37 chairs from the corpus (which were used in the system's development), with a precision of 94%; (ii) and 9 existing chairs (which were not used in the system's development), with a precision of 90%.

Lastly, the synthetic test assessed that ChairDNA was able to generate new designs, including 91% of the multipurpose chair types described in the **Multipurpose Chair Ontology** that were not represented by any design of the **Multipurpose Chair Sample**.

Fourth Research Question

> *What is the practical applicability of a design tool that is able to generate several types of designs, to the concept phase of the product design process?*

ChairDNA was evaluated by three groups of users: (i) 19 design students; (ii) 10 design practitioners, and (iii) 1 system developer (who is herself a designer). Design students evaluated ChairDNA 1.1 and design practitioners evaluated ChairDNA 1.2, as detailed in the chapter **User Evaluation of ChairDNA.** The benefits of using ChairDNA as a design tool in early concept design phases are, according to the users:

1) Quick and effective means of generating designs adequate to the anthropometric standards;
2) Quick and accurate visualization of the design during the generation process;
3) Quick and easy means of transforming designs;
4) Suggestion of unexpected (or even impossible) solutions;
5) Easy to learn and to use (it does not require experience in chair design and/or 3D modelling);
6) Easy generation of design families and/or design styles;
7) Generation of an editable 3D model in three possible CAD applications.

The first five points were mentioned by both the design students and design practitioners and the last two are observations of the developer. On another hand, the users also mentioned some disadvantages regarding the usage ChairDNA as a tool for the concept phase of chair design:

1) Restriction to a low level of shape detail;
2) Restriction to a specific product type (i.e., to multipurpose chairs, although ChairDNA can also generate stools and tables);
3) Support a task in which the designers are already good (although it systematizes some recurrent design patterns);
4) Lack of imprecision, fluidity and intuitiveness when compared to freehand sketching (since the interaction is not made directly in the shape but on representations of fragmented parts);
5) Danger of the solution being regarded as an end product, particularly by inexperienced designers. In fact, it is not ensured that the designs generated by the tool are stable or even comfortable (although the designs are restricted to anthropometric standards).

The first two points were mentioned by both the design students and design practitioners and the last three are observations of design practitioners. The poor efficiency of the ChairDNA prototype was also criticized by all the users.

While some of the aforementioned advantages and disadvantages were overall consensual, others were more controversial, since the participants provided some contradictory opinions:

1) Some participants argued that, since the tool can only produce combinations of existing chairs, it is not capable of generating truly creative, unexpected solutions. However, other participants (and the developer) denoted that ChairDNA can surprise the user with unanticipated results;

2) Since the tool is intended for the concept phase, the output designs are intermediate stages of a solution, and thus are inaccurate and incomplete. However, the majority of the participants would prefer more shape detail (only one participant mentioned that the current level of detail was excessive). On another hand, some designers regretted the absence of the inaccurate side of freehand sketching. One solution for this apparent contradiction, suggested by one participant, would be to have of two generation modes: one more precise and other more imprecise.

3) The participants considered that the tool limits decision-making, which was regarded as a disadvantage by the majority of the participants but, as mentioned by one user, may also be considered an advantage. ChairDNA is restricted to the design of multipurpose chairs, which on the one hand disallows the designer to radically change the shape of the chair (that would be a reasonable thought since the chair is the cause of many back pain problems in Western societies), but on the other hand ensures that the designs are suitable to the human body in an upright sitting position.

8.2.2 Secondary Findings

The development of the computational model led to some secondary findings, regarding the utility of grammar-based systems as design tools, description tools, analysis tools, and programming tools.

Grammar-based design tools can be used within different design strategies. In the user evaluation of ChairDNA, the main task proposed to the participants (design students and practitioners) was to develop a 3D digital model of an original multipurpose chair, using the tool. The design task was accomplished by 84% of the students (three did not use the tool to generate the solution) and by the practitioners with a completion of 95% (one did not develop an original concept and other did not complete the design). ChairDNA was mainly used by the participants following three different design strategies: (i) design a solution from scratch (by freely explore the solution space), (ii) design a solution from a predefined idea (of the designer), (iii) and redesign an existing solution (of another designer). Few participants attempted to (iv) reproduce a given design. The design students used other tools beyond ChairDNA (e.g. drawing and modelling).

The practitioners, in addition to the design task, also had to perform a reproduction task, which was the most difficult and time-consuming one, and a transformation task. On average, the participants reproduced 71% of a given design (the **214** chair), while 95% completed some requested transformations on another given design (the **Gonçalo** chair).

Grammar-based design tools benefit from being coherent with the designer's creative process. Some characteristics of the designer's process (detailed in the chapter **User Evaluation of ChairDNA**) can be supported by ChairDNA, while others cannot: (i) ChairDNA is used along with CAD software and is intended for the concept phase; design practitioners use CAD software in the concept phase somewhat less than in other design phases, while design students rarely use CAD software in early concept phases; (ii) ChairDNA can facilitate the generation of design collections, which is a common task in chair design; (iii) ChairDNA addresses functional and formal constraints (which are commonly defined by the designer), but not symbolic and practical constraints (being the first typically defined by designers and the latter imposed by the design brief); (iv) ChairDNA supports an exploratory process, typically used in design practice; (v) ChairDNA supports additive and transformation processes, but not the continuous fluid process inherent to freehand drawing; (vi) ChairDNA allows the designer to depart from existing chairs and/or design styles, which commonly influences the designers along the design process; (vii) ChairDNA allows the user to start the generation by the Legs or the Seat, but not by the Back; (viii) ChairDNA provides guides similar to the ones used by some designers in their process; (ix) ChairDNA can aid the designer in the generation of several alternatives (which is considered a critical feature in the concept phase), but not with the selection of alternatives. It was acknowledged that, in general, the more coherent the tool was with the users's process, the greater the satisfaction degree of the user.

Shape emergence in grammar-based design tools is not a key feature for generating unanticipated solutions. The emergence in computational design systems is regarded as a key feature for generating creative, unexpected solutions. Set grammars do not contemplate *emergent shapes* (derived from subshape detection), but, although not comprising ambiguity in decomposition, they comprise ambiguity in rule application (since a given rule can be applied in different parts of a design). Meanwhile, the implementation methodology dictated the removal of all the ambiguity (in order to reduce problems of efficiency, utility and usability), meaning that MCG comprises rule application ambiguity while ChairDNA does not. However, this was not impeditive for the ChairDNA tool to generate solutions regarded as unexpected by the users. Ultimately, emergence and creativity are inherent to the user, which, for instance, may perceive *emergent meanings* in the designs (as observed in the chapter **The ChairDNA Design Tool**).

In grammar-based design tools, the solution space of a random automated generation should be more restricted than the one of a manual human generation. ChairDNA 1.2 encompasses a manual generation mode and a random generation mode. Currently, the manual mode is unrestricted, while the random mode is restricted to the generation of multipurpose chairs. Without this restriction, the random mode would produce highly incomplete designs, since it could not recognize a final design as being a chair, a stool, or a leg. Meanwhile, the random mode is still highly unrestricted; because it is using the same ranges of the manual generation, random designs are much more extravagant and somehow unexpected than human generated designs (as illustrated in the chapter **The ChairDNA Design Tool**).

Grammar-based analysis tools comprise the ability to:

1) *Infer characteristics of design styles.* The individual styles of the designers Daciano da Costa and Jasper Morrison were roughly compared through the analysis of grammars rules and parameters. It was found that Daciano uses more geometric shapes and rigid proportions than Morrison, which may explain why the Daciano Chair Grammar uses significantly less parameters than the Jasper Chair Grammar. However, styles were incompletely defined, since the grammars did not address slight curves, materials, colours, and other key features that contribute to identify a style.

2) *Infer characteristics of a designer's process.* The process provided by the design system is similar to the process employed by the author of the designs upon which the system was developed. The first version of the **Multipurpose Chair Grammar** was developed upon the analysis of a corpus of designs of the designer Daciano da Costa. The process of the designer and the one provided by the grammar both employ compositions of lines, surfaces and volumes, and the designs are the result of an addition of autonomous components. This relation between the grammar method and the designer's method was not intentional; it was verified *a posteriori*, which might suggest that the analysis of a set of designs of one individual may indicate *per se* clues of his/her design process.

3) *Infer the formal resemblance of a design with a given style.* The level of the formal resemblance of a given design with a specified design style can be inferred from the extent to which a design can be generated by a specific grammar (whose language addresses the style). This was suggested by the results of the analytic test described in the chapter **The ChairDNA Design Tool**.

Grammar-based systems are suitable programming tools to be learned and used by designers. Designers in a near future will tend to embrace programming skills in their design practice (as mentioned in the **State of the Art** chapter). To this end, shape/set grammars have proven to be valuable devices for designers that do not have an extensive programming experience to develop logical reasoning around a visual vocabulary.

8.3 Contributions

The contributions of this research are divided into two categories: (i) main contribution, addressing the hypothesis previously described, and (ii) secondary contributions.

8.3.1 Main Contribution

The major contribution of this research is a computational model, which is translated into a grammar-based design tool for the concept phase of multipurpose chair design. The tool is able to generate a large variety of designs within a product class – which ultimately, is argued to have a practical application in real-life design scenarios.

8.3.2 Secondary Contributions

The secondary contributions are described below, for each of the chapters related to the characterization of the computational model.

Multipurpose Chair Sample

Brief review of Modern chair design: succinct overview of Modern chairs (designed from 1850 to the present), comprising a particular emphasis in Portuguese chair design, in the designers Daciano da Costa and Jasper Morrison, and in the Thonet GmbH manufacturing company.

Five databases addressing subpopulations of Modern seats: (i) 53 seats authored by the Portuguese designer Daciano da Costa (sourced from a retrospective exhibition); (ii) 55 seats authored by the English designer Jasper Morrison (sourced from its official web page); (iii) 639 Modern iconic seats (sourced from two design museum collections and four Modern chairs compendia); (iv) 85 Modern seats of Portuguese designers (sourced from four design exhibitions, two design competitions and one Portuguese design compendium); and (v) 6 chairs manufactured by the German company Thonet GmbH (sourced from the corpus of a grammar-based system). The databases contain information about the designer, the design date, the producer, and the product type.

One database addressing a sample of Modern multipurpose seats: including 46 chairs and 1 stool, selected from the aforementioned subpopulations databases: (i) 6 wooden frame chairs designed by Daciano da Costa; (ii) 6 wooden frame chairs designed by Jasper Morrison; (iii) 32 iconic chairs (including 1 Portuguese iconic chair) and 1 stool, comprising a large variety of types (two of these chairs are repeated); and (iv) 4 chairs from a design family manufactured by Thonet GmbH. The database contains several information about design and production details, functions, materials and technologies, dimensions, product type, recyclability and packaging, and related products.

Multipurpose Chair Ontology

Multipurpose Chair Ontology: the main contribution of this chapter is an ontology which systematizes knowledge in the domain of multipurpose chairs, through a classification of concepts, their properties and relations. The ontology encompasses a definition of terms, an overall coherence, supports different abstraction levels and is extendible to further conceptualizations. Moreover, it can be used to generate new solutions. The ontology is currently divided into two sections. The first section comprises a formal ontology represented in three formats (schemas, descriptions and diagrams), and addressing four main classes: (i) *parts* (describing 39 functional parts distributed along 6 groups of parts); (ii) *geometry* (describing size, position and shape parameters); (iii) *types and styles* (describing about 100 types of chairs and some styles); and (iv) *generation* (describing an additive generation sequence of the chair parts). The second section comprises a less formal ontology, addressing two main classes: (i) *functions* (describing primary, practical, formal and symbolic functions), and (ii) *materials* (describing materials, manufacturing technologies and physical properties).

Meta-Ontology: an ontology generalized from the Multipurpose Chair Ontology, comprising three main classes (*parts*, *geometry*, and *types*). This ontology can also be, in theory, applicable to other product classes.

Design Ontology: the Multipurpose Chair Ontology was particularized to the chair **214** (manufactured by Thonet GmbH), as a case study, but can also be applicable to other particular designs.

Multipurpose Chair Grammar

Multipurpose Chair Grammar (MCG): the main contribution of this chapter relies on a parametric set grammar for multipurpose chair design, comprising 108 rules and 61 parameters. The grammar is intended to be used as a tool for the concept phase of chair design, and is capable of describing and generating a large diversity of designs.

Seven sub-grammars: the following grammars were particularized from the MCG:

1) *Daciano Chair Grammar* (DCG): a specific grammar which characterizes the individual style of the designer Daciano da Costa;

2) *Jasper Chair Grammar* (JCG)*:* a specific grammar which characterizes the individual style of the designer Jasper Morrison;

3) *Thonet Chair Grammar* (TCG): a specific grammar which characterizes a design family, manufactured by the company Thonet GmbH;

4) *Iconic Chair Grammar* (ICG)*:* a specific grammar which characterizes the large diversity of design types observable in iconic Modern chairs;

5) *Daciano-Jasper Hybrid Grammar* (DJHG): a hybrid grammar resulting from the union of DCG and JCG;

6) *Daciano-Jasper Common Grammar* (DJCG): a common grammar resulting from the intersection of DCG and JCG;

7) *Synthetic Chair Grammar* (SCG): a complement grammar, comprising the features of the MCG that are not included in any of the previously mentioned sub-grammars.

Meta-Grammar: a generalization of the MCG. The Meta-Grammar ensured the overall coherence and completeness of the MCG and simplified its implementation. Moreover, it can, in theory, be applicable to other grammars addressing other product classes.

Four methods for generating sub-grammars: (i) generating a specific grammar from a generic grammar; (ii) incorporating an existing specific grammar into a generic grammar; (iii) generating a common grammar from overlapping specific grammars; and (iv) generating a hybrid grammar from overlapping specific grammars. The methods were applied, respectively, in the development of (i) DCG, JCG and ICG; (ii) TCG; (iii) DJCG; and (iv) DJHG.

Two methods for generating generic grammars: (i) from the analysis of a corpus of designs comprising different types (the less similar the designs of the corpus, the more generic is the grammar) and (ii) from the union of two specific grammars. The methods were applied, respectively, in the development of (i) ICG and (ii) DJHG. It was verified that, although the first method resulted in a higher number of rules, it did not ensure the prediction of all design types.

A method for testing the generative capabilities of generic grammars: the descriptive, analytic and synthetic tests, which evaluate the ability of a grammar in generating designs (corpus designs, existing designs, and new designs), were extended to evaluate the ability of a generic grammar in generating specific grammars (grammars from the corpus, existing grammars, and new grammars). These tests were successfully applied to the MCG.

Classification of shape grammars: a theoretical framework was developed for the classification of the MCG. Meanwhile, this framework can be applied in the classification of other grammars.

The ChairDNA Design Tool

ChairDNA design tool: the major outcome of this chapter is the ChairDNA digital design tool. Two main versions were developed (1.1 and 1.2). ChairDNA is able to generate a large variety of multipurpose chairs within the necessary anthropometric restrictions. Using ChairDNA 1.2, designs can be generated from scratch, from editing a given template, or from automatic random generation. ChairDNA provides a simple interface oriented for designers, which does not require specific knowledge on shape grammars, programming or 3D modelling. ChairDNA constitutes a step for overcoming the lack of available digital tools for the early concept phases of the design process.

Beyond the contribution of ChairDNA as a design tool, it has also proven to be useful regarding other usages: (i) as a *description tool*, ChairDNA allows the description and storage of the shape and structure of a chair, and thus it could be used, for e.g., for historic preservation; (ii) as an *analysis tool*, ChairDNA can provide an aid in the identification of styles, in assess the similarity degree between designs, and in the classification of designs; furthermore, it can easily identify whether the dimensions of a given design follow certain anthropometric standards. Lastly, (iii) as a *pedagogical tool*, ChairDNA can be useful to teach anthropometrics, design types, and relations between parts.

A methodology for implementing set grammars: comprising the translation of rules and parameters into user interface elements. The methodology was successfully applied in the implementation of the MCG into the digital tool ChairDNA, and can be applied to the implementation of other grammars. ChairDNA highlights the rules and parameters available at each generation step, and automatically computes their application. Moreover, it allows testing the grammar and enhances generation speed and accuracy. The methodology contributes to overcome the lack of (i) clear implementation methodologies, and (ii) implementations of design grammars.

A methodology for implementing sub-grammars: the procedure was applied to calculate the implementation values of the seven aforementioned sub-grammars. Although these values were not implemented in ChairDNA, a mock-up of the envisioned interface was displayed.

A method for testing the generative capabilities of generative systems: the descriptive, analytic and synthetic tests, employed to assess of the generative capabilities of analytic grammars, were adapted to the evaluation of analytic generative systems. The tests were complemented with a completeness test, which calculates the extent to which the system is able to generate corpus designs and existing designs. Moreover, the extent to which the system is able to generate new types of designs can also be calculated. The three tests were successfully applied to ChairDNA, addressing design styles, design types, design collections, and random designs.

User Evaluation of ChairDNA

User Evaluation of ChairDNA: the main contribution of this chapter was the evaluation of the usability and utility of the ChairDNA design tool, comprising its strengths and weaknesses. Two groups of participants (Portuguese design students and design practitioners) respectively evaluated the two main product versions (ChairDNA 1.1 and ChairDNA 1.2).

A methodology for the evaluation of design tools: the evaluation protocol and methods developed for the aforementioned experience can be used for testing other design tools.

Improvement of ChairDNA: the evaluations also contributed for the improvement of the tool; ChairDNA 1.2 implemented 73% of the recommendations of the first evaluation, and the second evaluation resulted in a recommendations list for future program versions.

A survey about the usage of CAD software by Portuguese designers: concerning what software the design students and practitioners use, in what design phases, and for what design tasks.

A survey about the chair design process of ten Portuguese designers: giving a particular emphasis on the form generation process. This survey contributes for the lack of studies describing in detail the concept phase of the chair design process.

8.4 Future Work

The recommendations for future work, divided by each chapter related to the development of the computational model, are listed below.

Multipurpose Chair Sample

Extend the database: with the development of the ontology, the sample should be extended accordingly, in order to include (i) new classes and (ii) new chairs.

Implement the databases: an accessible and editable database would permit to: share the data, edit and complement the data; visualize data more flexibly, obtain features lists, and search for designs with specific features.

Multipurpose Chair Ontology

Formalize the section two of the ontology: comprising a higher systematization of functions and materials.

Extend the ontology: include other features, such as a higher level of shape detail, connections between parts, and other generation processes (which presupposes to learn more about the chair design process).

Implement the ontology: an accessible and editable ontology would permit to: share the knowledge, edit and complement the knowledge, support multiple representations (including schemas, descriptions and diagrams), connect the system to the database, and include automatic learning capabilities.

Multipurpose Chair Grammar

Extend the grammar: add rules and/or parameters addressing a higher level of shape detail, connections between parts, and position of solid parts. Furthermore, it is recommended to extend the grammar language (in order to address other furniture items beyond multipurpose chairs) and to include further descriptions (such as materials).

Test the grammars: undertake further tests on the grammars: (i) test the MCG by including other existing specific grammars (*analytic test*); (ii) test the MCG by generating other new specific grammars (*synthetic test*); and (iii) test the Meta-Grammar by applying it to other grammars, addressing languages of other product classes beyond multipurpose chairs.

The ChairDNA Design Tool

Extend the language: include other multipurpose chair types (e.g. asymmetric chairs), other chair types (e.g. longue chairs), other seat types (e.g. benches), and other furniture types (e.g. dining tables).

Increase the level of detail: include a higher level of shape detail (e.g. add further curves and section shapes), stipulate the alignment of solid parts, and specify components (given by unions between parts) and joints.

Include templates: of materials and design types;

Edit and include automatic generation modes:

1) Restrict the spectrum of solutions generated by the random mode (by adding parametric ranges restrictions, stability restrictions and connectivity restrictions);

2) Include an automatic mode for generating: (i) design collections (from a given design) specific, common or hybrid styles (from a given set of designs), (ii) hybrid designs (from two or more designs), and (iii) new designs from a given style (applying the random mode to style restrictions);

3) Include an optimization mode, comprising an automatic selection of the best solutions in the light of certain design goals (e.g., less material, more resistant, or cheaper).

Include other commands (beyond generation):

1) *Description*: automatically import designs from a given 3D model, through value extraction (which could trigger an automatic generation of new rules);

2) *Analysis, simulation and evaluation*: include commands such as: weight calculation, stacking units calculation, structural analysis, environmental impact analysis (e.g. calculation of material waste), motion simulation (e.g. folding or stacking motion), comfort evaluation (considering that it is inherent to a specific user), cost evaluation, and aesthetic evaluation.

3) *Fabrication*: include manufacturing details and transposition to digital fabrication.

Improve the interface:

1) Include icons and tooltips;

2) Include the possibility to interact directly in the 3D model (for e.g. by dragging points or by 3D digital drawing);

3) Include the possibility for the user to customize the interface, for instance by allowing the edition of parametric ranges (e.g. import a set of anthropometric ranges) and the edition of nomenclature;

4) Improve the efficiency, i.e., the speed the program's feedback in response to user inputs.

Test the methodologies: (i) apply the implementation methodology to other set grammars; and (ii) implement specific grammars in ChairDNA.

User Evaluation of ChairDNA

Evaluate ChairDNA regarding different usages and users:

1) *Design tool*: perform user tests with designers of different nationalities (such as the designers of the chairs of the sample). The evaluation method could be reformulated, in order to include: (i) the evaluation of the resulting designs by experts (e.g. the jury of a design competition); and (ii) a comparison between one group of participants designing with ChairDNA *versus* other group of participants designing without ChairDNA or designing with the grammar tool;

2) *Pedagogic tool*: perform user tests with more advanced design students and other design teachers;

3) *Analysis tool*: perform user tests with design historians or design theorists. It is recommended to evaluate whether new designs generated in ChairDNA, that are claimed to belong to a given design style, actually resemble that style, by the authors of the style or by their collaborators;

4) *Customization tool*: perform user tests with end users. Regarding ChairDNA as a customization tool, it could include an option to resize a design in order to fit a particular user (e.g. considering its stature and weight), by displaying or not a parametric dummy;

5) *Fabrication tool*: perform user tests with manufacturers. Regarding ChairDNA as a fabrication tool, it could include an option to adapt a design to specific manufacturing constraints (e.g. dimensions of stock materials, machine constraints, and standardized components). Consequently, ChairDNA could shorten the adaptation of the project to the reality of the production. Moreover, it could eventually perform as a tool for the entire design process.

This research constitutes a step towards addressing a more significant impact of grammar-based tools in real-life design scenarios. The analytic and generative capabilities of such tools, as well as their usefulness for the concept phase of the design process, were illustrated within this research. Future developments are envisioned in this field of knowledge, namely in light of the wide range of possibilities provided by user's recommendations.

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