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MASS CUSTOMISATION IN THE FURNITURE DESIGN INDUSTRY: THE CASE OF THONET CHAIRS

Ramo de Doutoramento: Design

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Julho, 2015

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Abstract

The thesis proposes a model for mass customisation in the furniture design industry, with the purpose of improving the patterns of collaboration between the disciplines of design and engineering during the realisation of the design process, and in the definition of the production process. The ultimate goal is to enable the design of products that can be customised by an individual consumer according to his/her own idiosyncratic intentions.

The theoretical model is illustrated by its application to an iconic mass production problem – Thonet bentwood chairs – which was changed to comply with the paradigm of mass customisation.

The proposed model comprises the use of a generative design system and a production system supported by computer-aided design. It enables the characterisation, exploration, evaluation and production of custom solutions within a predefined design language.

The developed generative design system corresponds to the embodiment design phase of the design process. The development proceeds in two steps: in the first, the design language is codified by means of a shape grammar; in the second, it is transformed to expand the number of solutions generated.

The generative design system encompasses two subsystems: shape generation and shape evaluation. The shape grammar is implemented as a set of parametric design models to permit the interactive generation of customised variants. These customised variants become the input information to the shape evaluation subsystem, which comprises simulation and optimisation, to guarantee the structural feasibility of the customised chairs under operating conditions.

The conceptualised production system, corresponds to the detail design and production phases of the design process, in which the production process is formalised. It is proposed a reconfigurable tooling system for automated wood bending which directly reflects the requirements of the design process, the specificities of the product, and the constraints of the material.

Keywords
Mass customisation; Digital design; Shape grammars; Parametric design; Furniture design.

Resumo

A tese propõe um modelo para a *mass customisation* na indústria do design de mobiliário, com o intuito de melhorar os padrões de colaboração entre as disciplinas de design e engenharia, no decurso da realização do processo de design e na definição do processo de produção. O objetivo final é permitir o design de produtos que possam ser customizados por um consumidor final, de acordo com as suas próprias intenções.

O modelo teórico é ilustrado pela sua aplicação a um problema icónico da produção em massa – cadeiras Thonet realizadas em madeira dobrada – que foi alterado de modo a satisfazer os requisitos do paradigma de *mass customisation.*

O modelo proposto compreende o uso de um sistema de design generativo e de um sistema de produção, ambos suportados por design assistido por computador. O intuito é permitir a caracterização, exploração, avaliação e produção de soluções customizadas pertencentes a uma linguagem de design predefinida.

O sistema de design generativo desenvolvido corresponde à fase de concretização do projeto no processo de design. O seu desenvolvimento decorre em dois estádios: no primeiro, a linguagem de design é codificada através de uma gramática da forma; no segundo, esta é transformada para expandir o número de soluções geradas.

O sistema de design generativo compreende dois subsistemas: geração de forma e avaliação de forma. A gramática da forma é implementada como um conjunto de modelos de design paramétrico, de modo a permitir a geração interativa de variantes customizadas. Estas variantes customizadas são a informação de entrada no subsistema de avaliação de forma, que compreende simulação e otimização, de modo a garantir a fiabilidade estrutural das cadeiras customizadas em condições operativas.

O sistema de produção conceptualizado corresponde às fases de detalhe e de produção do processo de design, nas quais o processo de produção é formalizado. É proposto um sistema de máquina-ferramenta reconfigurável para permitir a dobragem automatizada de madeira. A sua conceptualização considera diretamente os requisitos do processo de design, as especificidades do produto e os constrangimentos do material.

Palavras Chave

Mass customisation; Design digital; Gramáticas da forma; Design paramétrico; Design de mobiliário.

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Glossary and Abbreviations[1]

***.xls**
Microsoft Excel file extension

2D
Two-dimensional

3D
Three-dimensional

3D Studio Max
Three-dimensional computer graphics software developed by Autodesk. It comprises modelling, animation and rendering capabilities, and it is used mainly for visualisation purposes across several industries.

ABS (Acrylonitrile Butadiene Styrene)
Thermoplastic polymer employed in the construction of moulded components.

AI
Artificial Intelligence

Algorithm
Step-by-step instructions that explains how to perform a predefined goal.

ATO (Assemble-To-Order)
Production strategy in which the basic components of a product are manufactured beforehand, but only assembled when the customer gives the order. It enables a certain extent of customisation and it is often associated with standardised customisation.

Axis
Reference element of the Cartesian coordinate system. Points in a two-dimensional space are specified by their distance to the X- and Y-axis, while in a three-dimensional space they are specified by the distance to the X-, Y-, and Z-axis. Besides the distances, the translations and rotations can be specified by referring to the axis.

B2B
Business-to-business

B2C
Business-to-consumer

bar
Unit of pressure (1 bar = 100 000 Pa).

Batch production
Production methodology characterised by the division of labour to produce groups (or batches) of the same component or product.

Body
In CATIA, a Body or PartBody is the default body available in the Part Design workbench.

C
Celsius, unit of temperature.

CAD (Computer-Aided Design)
General term which characterises computer software that assist designers, engineers, and architects in their activity, comprising a wide range of applications, from 2D to 3D applications.

CAE (Computer-Aided Engineering)
General term which characterises computer software that assist engineers in their activity of analysing, simulating, and optimising products.

CAM (Computer-Aided Manufacturing)
The use of computer software to control machines employed in the automated manufacturing of a product.

Casting
Forming production method involving the injection or pouring of a molten material into a mould comprising the required shape of the component or product.

CATIA
Acronym for Computer Aided Three-dimensional Interactive Application, which is a computer-aided design, engineering and manufacturing software developed by Dassault Systèmes. It enables feature-based modelling and it is used in several industries to assist the product development process, by enabling the modelling, the simulation, and the preparation of the automatic manufacturing of products.

CDM
Common data model

CIM
Computer-integrated manufacturing

[1] Underlined words refer to other terms explained in the present Glossary and Abbreviations

Clamp
Stationary workholding device comprising one or more moveable jaws that is employed to attach a workpiece.

CNC (Computer Numerical Control)
Machine tools operated by a computer. It requires CAD and CAM to define the operations performed by the machine tools.

CNC milling
Computer numerical control (CNC) machinery capable of handling heavy-cutting tasks, such as the ones involving metal and other solid materials. The cutting operations involve both the motion of the rotating cutter and the platform to which the material is fixed.

CNC routing
Computer numerical control (CNC) machinery capable of handling cutting tasks in softer materials, such the ones involving wood and plastics. The cutting operations involve only the motion of the rotating cutter, while the material and the platform to which it is fixed remain static.

Component
Individual part of a product.

Corner block
Intermediate component applied in a wooden product to join two wooden components together.

Crest rail
The top rail of the backrest of a chair.

CRM
Customer relationship management

CSIL
Centre for Industrial Studies

Decay
Rotting of wood caused by fungus.

deg
Degree, unit of angle measurement.

Design language
Set of designs generated by a shape grammar.

Design style
Set of formal and functional features shared by a set of designs.

Die
Tool with a predefined desired shape, used in cutting or stamping a specific component by force application into a solid material.

DIY
Do-it-yourself

DTO (Design-To-Order)
Production strategy in which the product is designed and produced according to the specifications of the customer. It is often associated with tailored customisation.

Economies of scale
When a company decreases the total cost of production by efficiently producing the same product in high volume.

Economies of scope
When a company decreases the total cost of production by efficiently managing its competencies, through a diversification of the products in its portfolio.

End-stop
Wooden block or clamp that prevent the wood from elongating more than 1%-2% during bending operations.

FDM (Fused Deposition Modelling)
Additive manufacturing process consisting in the extrusion of a molten material as a filament. The filament deposition creates the successive cross-sectional layers of the three-dimensional object until the predefined shape is achieved.

FEA (Finite Element Analysis)
Computer simulation technique used in engineering analysis to calculate the effects of loads on a given object, such as stress, deformation, temperature, or vibration. To perform the calculation, the given object is divided into a set of finite elements (FEM) which are then submitted to the effect of loads.

Feature-based modelling
Definition of a geometrical model using computer-aided design software which associates the features to the created model, such as dimensions and constraints, as a set of established relations. These features enable a single dimensional change to coordinate the modification of the whole geometry by maintaining the established relations.

FEM
Finite Element Method

Fixture
Auxiliary device for holding a workpiece in the required position during the manufacturing operation.

FMS (Flexible Manufacturing System)
Automated production system consisting in a group of several computer numerical control (CNC) machines connected to an automated material handling system working together to produce a product. The degree of flexibility

regards to the ability to accommodate change in the number of produced items and to be reconfigured to produce new types of products.

GA
Genetic algorithms

G-code
Programming language used in computer-aided manufacturing for the numerical control of automated machinery.

Generative Components
Computer-aided design software developed by Bentley Systems Incorporated. It enables the user both the direct manipulation of a three-dimensional model and the definition of the attributes and parameters through visual programming language.

Geometrical set
In CATIA, a geometrical set is the sub-set of a Body, containing a particular set of geometrical features.

GPa
Gigapascal, unit of pressure (1 GPa = 1 000 000 000 Pa).

Grain
The direction of the wood fibres.

Graph-based modelling
Definition of a geometrical model using a visual programming language which complements the three-dimensional modelling environment. The features that will define the geometrical model are established by using nodes and connections in a step-by-step procedure.

Grasshopper
Visual programming language developed by Robert McNeel and Associates that runs as a plugin in Rhinoceros software. Instead of direct manipulation of the geometry, users define the basic attributes and the parameters that will generate the final shape by using nodes and connections in a step-by-step procedure.

GSA
The Generative Structural Analysis workbench in CATIA.

GUI
Graphic user interface

Houdini
Three-dimensional computer graphics software developed by Side Effects Software. It comprises modelling, animation and rendering capabilities, and it is used mainly for visualisation purposes across several industries.

ICSID
International Council of Societies of Industrial Design

IF
Inner frame

IGES
Initial Graphic Exchange Specification

Injection moulding
Forming production method involving the injection of a molten polymer into a mould comprising the required shape of the component.

ISO
International Organization for Standardization

IT
Information technologies

Jig
Auxiliary device for holding a workpiece in the required position and for guiding it during the manufacturing operation. It enables the repetition of the performed operation under the predefined conditions.

JIT (Just In Time)
Management and production strategy in which the different stakeholders involved in the production cycle must accomplish their tasks in a precise time schedule in order to get the product to the market in the required quantities. It improves the efficiency of businesses by reducing the need for stock. It enabled the establishment of lean production.

kg
Kilogramme, unit of mass.

Laminate
Component made from thin sheets or strips of wood glued together.

Laser (Light Amplification by Stimulated Emission of Radiation)
Tool involving the optical amplification of light into a narrow beam to cut or melt materials.

Laser cutting
Subtractive manufacturing process consisting in using a laser to cut or engrave a material.

Law curve
In computer-aided design a law curve is a parametric curve whose X, Y and Z properties are controlled by user-defined equations.

LOM (Laminated Object Manufacturing)
Additive manufacturing process consisting in the bonding of successive layers of laser-cut paper until the final shape is achieved.

LP (Lean production)
Industrial model which improves mass production by enabling additional flexibility. This is achieved through continuous refinement of the product development process, by implementing a just-in-time production strategy and by improving information coordination in order to provide a greater diversity of products to consumers.

m
Meter, unit of length.

Machining
Subtractive manufacturing processes involving material removal to achieve a new configuration.

MAK
Museum für Angewandte Kunst

MC (Mass customisation)
Industrial model characterised by combining production efficiency with flexibility. The goal is to meet consumers' needs, to provide additional choice and to empower them to actively participate in the design process.

MDF
Medium Density Fiberboard

Method
A procedure for the act of designing.

Methodology
The process used to achieve a solution that solves an identified problem.

min
Minute, unit of time.

mm
Millimeter, unit of length (1 mm = 1/1000 m).

MOMA
Museum of Modern Art

Mortise
A part of a joint in woodworking. It is the hole or cavity cut in the wooden component to receive the corresponding tenon.

Mould
Tool with a predefined desired shape used in forming a specific component by pouring or injecting the material in a plasticised or liquid state.

MP (Mass production)
Industrial model characterised by the high-volume production of standardised products. The goal is to target large and stable market segments.

MPa
Megapascal, unit of pressure
(1 MPa = 1 000 000 Pa).

MTS (Make-To-Stock)
Production strategy in which products are produced for stock. Both production plans and required stock are decided according to the forecast of the demands. It is often associated with mass production.

N
Newton, unit of force ($1 N = 1 kg x m/s^2$).

NURBS (Non-Uniform Rational Basis Splines)
Type of spline commonly used in computer-aided design, in which each control vertex affect a local curvature of the spline.

OF
Outer frame

OSHWA
Open Source Hardware Association

OSI
Open Source Initiative

Pa
Pascal, unit of pressure (1 Pa = 1 N/m2).

Parametric model
Geometrical model defined by a set of relations between different features and that accommodates dynamic change by varying the numerical values of one or more parameters.

Part
Subset of a subsystem which performs a specific sub-function.

PC
Personal Computer

PEO
The Product Engineering Optimizer workbench in CATIA.

PFA
Product Family Architecture

Plasticisation
Step of a forming production process involving the alteration of the properties of a solid material to enable additional plasticity. The goal is to enable the forming of the material into the desired shape in the subsequent step.

PLM
Product Lifecycle Management

Plywood
Laminated board, made from wood veneers glued together and pressed to provide strength to the resulting board.

PM
Parametric design model

PM1
The first implementation of the parametric design models.

PM2
The transformation of the parametric design models.

Production cycle
The sequence of the processes involved in transforming an idea into a marketable product. It comprises design, fabrication, assembly, marketing, and distribution.

R&D
Research and Development

Retort
Steam pressurised chamber employed in the preparation stage of bending operations, in order to enable the plasticisation of wood.

Rhinoceros
Three-dimensional computer graphics and computer-aided design developed by Robert McNeel and Associates, which enables free-form modelling.

Rig
In computer graphics, a rig is the skeleton structure of the three-dimensional digital models, usually defined to setup motion. A hierarchical structure defines the relations between the different constituents of the control elements. The simplified structure is then related to the geometric mesh in order to control its deformation behaviour.

rt
Ratio

SA
Simulated annealing

Scarf joint
Woodworking method to fit two elements together by cutting opposing tapered ends on each element. The goal is to guarantee a visual continuity of the resulting element.

Schema
Simplified representation of a design or a design rationale.

SF
Seat frame

SG
Shape grammar

SG1
The first development of Thonet shape grammar.

SG2
The transformation of the Thonet shape grammar.

Shake
Wood defect characterised by fissures in the structure of the wood.

Shim
A tapered piece of material that fills a gap to allow for a tight fit between component and mould.

SLA (Stereolithography)
Liquid-based additive manufacturing process. It consists in curing a photopolymer resin with a ultra-violet laser until the final shape is achieved. The process creates the final shape in successive layers directly by taking the input from a three-dimensional digital model.

SLS (Selective Laser Sintering)
Powder-based additive manufacturing process. It consists in using a laser to fuse particles of the powder material. The process creates the final shape in successive layers directly by taking the input from a three-dimensional digital model.

Solid model
An enclosed solid geometric model.

SolidWorks
Computer-aided design, engineering and manufacturing software developed by Dassault Systèmes. It enables feature-based modelling and it is used in several industries to assist the product development process, by enabling the modelling, the simulation, and the preparation of the automatic manufacturing of products.

Specification Tree
In CATIA, the specification tree contains the all the operations used to create any element in the modelling environment.

Stage
Sets of steps that attain a sub-goal in a process.

Stamping
Forming production process employed in the fabrication of metal components. It consists in pressing the metal sheet into a die or mould enabling its cutting or shaping.

STEP
Standard for the Exchange of Product Model Data

Step
Subset of a stage that attains a specific sub-goal in a process.

STL
STereoLithography is the file extension used to enable the production of three-dimensional models using additive manufacturing processes.

Stochastic optimisation
Optimisation method involving a degree of randomness in the search for an optimal solution.

Strap-and-stop
Auxiliary apparatus to prevent wood from fracturing during bending operations involving smaller radii. It comprises the clamping of tensile steel straps and end-stops to the wood. A metal strap is placed against the convex side of the wooden piece in order to absorb the tensile stress produced by the bending, while slightly reducing the compressive stress on the concave side.

Stretcher rail
Component that connects the legs of a chair, to improve the stability of the chair.

Subsystem
Subset of an overall system which performs a sub-function.

Surface check
Wood defect characterised by fissures in the wood fibres observed in the flat surface of a wooden board.

Surface model
A geometric model with no thickness.

Sweep
In computer-aided design a sweep is the modelling of a surface by sweeping a profile along a specific curve.

System
Mechanism in which the constituent parts interact to achieve a certain goal.

Technique
A procedure for the act of designing using tools.

Tenon
A part of a joint in woodworking. It is the tongue of a wooden component that fits in the corresponding mortise.

Tooling
Customisation of a machine tool with specific mechanical equipment to enable the production of a specific geometry, component, or product configuration.

Torque
Amount of force involved in rotating an object within its axis.

Turning
Subtractive manufacturing process which uses a lathe, which is a machine tool that rotates the block of material while a tool removes material until the final shape is achieved.

V&A
Victoria and Albert Museum

Variant
Further differentiation of a predefined design solution or version by detailing specific features, such as dimensions.

Veneer
Thin sheet of wood. Face veneering refers to the application of veneers for decorative purposes, glued or nailed to the face of wooden boards.

Version
An alternative design solution within a design language or a design style defined by a designer.

Water-jet cutting
Subtractive manufacturing process consisting in applying high-pressure water through a nozzle to cut a material.

Wireframe model
Representation of a three-dimensional object using points, lines and curves.

Workbench
A specific CATIA environment featuring a set of tools to perform design tasks in a particular area of the product development process

1. Introduction

This chapter introduces the research context. It begins by characterising the research in light of the existing design research taxonomy. It then presents the investigation context and identifies the associated research questions. Following this, the research goals are presented and the thesis contributions listed. The chapter ends by delineating the structure of the thesis.

1.1. Position in Design Research Taxonomy

"It is when research activity is carried out through the medium of practitioner activity that the case becomes interesting. There are circumstances where the best or only way to shed light on a proposition, a principle, a material, a process or a function is to attempt to construct something, or to enact something, calculate, explore, embody or test it" (Archer, 1995, p. 11).

The ultimate goal of this study is to establish a design model for mass customisation in the furniture industry. The research falls into the category of design praxiology, the "study of the practices and processes of design"; and design phenomenology, which focuses on the "study of the form and configuration of artefacts" (Cross, 1999, p. 6). Due to the contemporary nature of the phenomenon, the methodology comprises action research by means of a case study (Yin, 1994 [1984]).

The scope and strategy of the investigation reflect the motivation of the researcher. The aim is to combine the propositions and findings systematically developed through academic research with the potential for future industrial applications. This principle ensures a symbiotic iteration between the scientific underpinnings of the work and empirical knowledge. The contribution of this study to design as a discipline involves the development of a model to support the design of customised products that meet user expectations with regard to utility and significance.

1.2. Research Context

1.2.1. Mass Customisation Processes

The processes of design, production and acquisition of physical artefacts encompass the dynamic relations between designers, manufacturers, and consumers. On a macro level these relations are influenced by the economy, technology, culture and policies, whereas on a meso level these frameworks enable specific industrial models to be established, which are then translated into systematic methods on a micro level.

Toffler's scenarios anticipated the emergence of new relationships between stakeholders in the design process (1970; 1989 [1980]). The author envisaged that the development of computer technology would have a significant impact across social structures. In the final decades of the 20th century and the first decade of the 21st century, developments in computing have transformed the following: the design process, by allowing for greater integration of information created in the different steps and by different disciplines; the production process, by providing quality and variety at lower costs; the market, now mediated through service-based relations; the acquisition process, by enabling the consumer to play an active role in the design process.

Mass customisation (Davis, 1987; Pine, 1993) has been established as the industrial model that best responds to the above-mentioned transformations. Craft-based principles such as diversification, closer relations with individual consumers and requirement-oriented production are combined with industrial postulates such as production efficiency, integration of processes and improved logistics. Companies operating under this industrial model must continually refine organisational processes in order to achieve the desired balance between the extent of product customisation, the robustness of internal processes, and fulfilment of consumer expectations (Salvador et al., 2009). Although transformations create novel sets of practices and relations, it must be noted that they supplement the existing scenarios rather than replace them (Heskett, 2002, p. 7).

The role of product design within a company can be analysed by two interconnected functions: 1) design definition and 2) the design process (Dormer, 1998 [1993], p. 9). Design definition involves design activity in shaping the characteristics of the artefact, embodying external factors in product features. The design process requires collaboration in terms of defining the manufacturing and marketing functions.

Mass customisation determines new requirements for the design process in comparison to mass production, which can be summarised as four main issues.

1. The first is expressed in the conceptual design phase (Pahl et al., 2007 [1984], p. 130). During this phase concepts are created to translate the specifications contained in the briefing. This issue is related to the development of methods to effectively translate user needs into product characteristics and evaluate them against the initial goals. Co-design strategies may be used to develop requirements and evaluate concepts.
2. The second emerges during the initial steps of the embodiment design phase to create a customisable preliminary layout. After defining the product's features and its general configuration, designers must specify the customisation space. This issue is related to the methods used to achieve a coherent identity across the product design language and the extent of any variation. In addition, these decisions must be formalised so that they can be communicated to subsequent steps of the design process.
3. The third issue is inherently related to the previous one and is established in the last steps of the embodiment design phase to create a definitive layout. The definition and refinement of the envelope of solutions must consider the company's fabrication

requirements, and the customised product under operating conditions. The activities to develop the definitive layout are directly associated with information sharing between the design and engineering disciplines with a view to achieving a viable solution based on input from both disciplines.

4. The fourth issue posed by mass customisation is the robustness of the design process. The need for flexible product development requires closer collaboration between activities which often take place in concurrency. Furthermore, information exchange and reuse becomes a fundamental asset in the refinement and iteration of both products and systems.

This thesis addresses the issues described in the last three points.

Research in mass customisation can be classified under two major categories: strategic management models and implementation models (McCarthy, 2004). The former established the research field in the 1990s through its grasp of the organisational principles that companies should pursue in order to deal with the uncertainties of the market. The latter focuses on the operational side of the strategies. Research in design and manufacturing processes fits into the second category. It proposes models and methods that enable a current strategy to evolve into one better suited to mass customisation principles.

Given the ongoing evolution of the methods, processes and disciplines involved, several possible combinations can be used to define models for mass customisation. Therefore, in order to define the research and its boundaries, some variables must be established in order to assess the extent of the transformation of certain specific variables. In addition, this requires an explicit position on the design process and the relationship between the different disciplines involved.

The sequence of activities in the design process can be regarded as dependent, independent or interdependent (Eppinger et al., 1994). Multidisciplinary research differs from dependent or independent approaches, by focusing on a single discipline with little or no interaction with others. An interdependent approach to the design process requires interdisciplinary research and addresses the boundaries between different disciplines. It relies on a level of concurrency of activities and collaboration between disciplines, thereby creating an interplay of information transfer during the establishment and realisation of the design process.

This thesis addresses the interdisciplinary problem in the collaboration between design and engineering, in order to create an integrated design process. However, there is a primary focus on design discipline.

1.2.2. Mass Customisation Implementation Strategies

Modularity has become the main implementation strategy for mass customisation (Duray et al., 2000) and derives from a reconfiguration of mass production plants. Design is centred around modular product architecture, which requires the definition of stable interfaces to accommodate different components (Ulrich & Tung, 1991). Customisation is combinatorial and accomplished by selecting from amongst the available building blocks. From a manufacturing perspective, standard modules can be produced in long runs. Custom modules can be produced using flexible manufacturing systems (FMS), which are often used to create variety by changing the colour, finish and materials attributes. These conditions respond to the requirement to achieve economies of scope. Consumers become involved in the production cycle during the assembly stage, at the end of the cycle, leading to a shorter customisation extent.

The use of computer-aided design (CAD) and manufacturing (CAM) integrates the design and manufacturing processes. This principle, combined with the widespread use of computer numerical control (CNC) machinery has allowed for a greater degree of customisation in comparison to modular strategies. Strategies using CAD-CAM technologies have been implemented using subtractive and additive manufacturing processes (Figure 1).

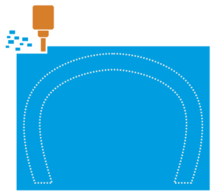
Gros (2001) proposed a methodology for implementing mass customisation in the furniture design industry, based on subtractive manufacturing. The author analysed the production of flat board materials using three-axis computer numerical control machines and how this could improve the design process. The result was the translation of traditional woodworking joints into digital joints optimised for the machining operations. These variables were then used to develop a range of customisable furniture designs.

Additive manufacturing processes offer the theoretical possibility of a higher degree of customisation, since the geometry is directly produced from digital representation, thus requiring less post-processing. In the previous decade this was the focus of a few experiments in the furniture design industry (Williams, 2006). However, the current state of the art does not respond to mass customisation requirements: only a limited number of machines of the size required to produce items of furniture have been adopted, production cadence is low and the cost of each item is high.

This thesis is based on the principle that between the two opposite ends of the spectrum of existing manufacturing processes there is the possibility that forming manufacturing systems can be developed to implement mass customisation by creating reconfigurable tooling systems.

CLASSES OF MANUFACTURING PROCESSES

SUBTRACTIVE



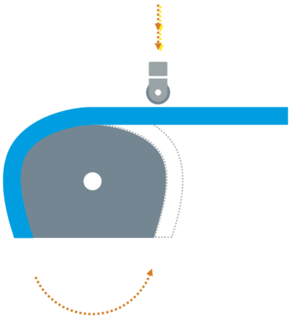
Definition

The process removes material to create the object.

Operations / Most common processes

Profiling: Laser cutting, Water-jet cutting, Plasma cutting.
Machining: CNC milling*, CNC turning.

FORMING



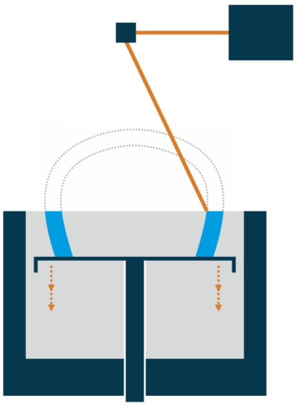
Definition

It requires tooling. The material changes its properties during the process, in which it is conformed to the mould/die to acquire the shape of the object.

Materials / Most common processes

Wood: Bending*, Laminating.
Plastic: Injection moulding, Thermoforming.
Metal: Sand casting, Die casting, Tube bending.

ADDITIVE



Definition

The process joins successive layers of material to create the object, directly from a digital 3D model.

Types / Most common processes

Solid-based: Fused Deposition Modelling (FDM).
Liquid-based: Stereolithography (SLA)*.
Powder-based: Selective Laser Sintering (SLS).
Laminated-based: Laminated Object Manufacturing (LOM).

* Process diagrammed on the left

Figure 1. Classes of manufacturing processes (adapted from Thompson, 2007)

1.3. Research Questions

Mass customisation requires a redefinition of design activity, which can be summarised under its two interconnected dimensions. In terms of design definition, it involves developing methods which provide better support for the definition of product characteristics and their associated solution space for customisation. With regard to the design process, it is necessary to integrate the various disciplines and improve the information flow between design and engineering in the embodiment design, detail design and production phases. The goal is to achieve a seamless level of collaboration between the design process and the manufacturing process.

Digital design tools help to integrate the different steps and disciplines involved in the product development process. Their contribution to design definition involves the possibility of assisting the designer in generating multiple alternatives from a unique model through the use of computer-aided design. In terms of the design process, new patterns for interdisciplinary approaches can be envisaged. Integrating computer-aided design with engineering (CAE) and manufacturing enables the design variables to be formalised throughout the different steps of the design process. The interchange of digital information enables mass customisation strategies to be implemented.

The following questions establish the fields for the research undertaken in this thesis.

1.3.1. Design Definition

With regard to design definition, this thesis focuses on the activities developed in the embodiment design phase. In this phase, using design methods to create formal synthesis (Bonsiepe, 1992, p. 221), a concordant set of rules must be created to determine the formal identity: a) between different elements of a design, in the case of a unique product; b) between different designs in the creation of a product family.

In the case of mass customisation these specifications must allow for a range of variation whilst still maintaining coherence. Considering the use of digital tools and their capacity to generate multiple outputs, it has become possible to investigate change of shape in given circumstances. However, the following open questions remain:

1. How can tacit knowledge be translated into explicit knowledge?
2. How can explicit knowledge be encoded into digital software?

According to Nonaka (1991, 1994) creating new knowledge in the context of organisations depends on the ability to convert tacit knowledge into explicit knowledge, by externalising the former. Tacit knowledge relies on individual and empirical experience while explicit knowledge can be formalised and systematised. These premises can be applied to the design process, by considering that implicit decisions made in the conceptual design phase must be formalised in order to become explicit in the embodiment design phase, so that they can be communicated to other disciplines involved in the design process. Given this purpose, in the light of mass customisation requirements, tacit knowledge must be formalised into explicit knowledge which systematises the generative procedures. Shape grammars (Stiny & Gips, 1972) provide a formalised method for encoding the generation procedures of a design style. In addition, they enable both formal and functional-related aspects to be represented (Stiny, 1980). For these reasons, shape grammars are employed in this research to address the generation problem, allowing aspects of tacit knowledge to be converted into explicit knowledge that can be used to guide the subsequent steps of the design process.

The second question is not fully unravelled by shape grammars, since difficulties associated with its implementation have been observed in the literature (Gips, 1999). This study contributes to the field by developing methods for using shape grammars to define a design process to implement a tailored customisation strategy in the furniture industry.

1.3.2. Design Process

With regard to the design process, this research aims to improve the relationship between the design and engineering disciplines in order to establish a generative design system for mass customisation. The creation of reliable information generated by design knowledge and its communication to subsequent steps of the design process can be assisted by the use of digital tools. Despite this possibility, if shape reconfiguration becomes an intrinsic aspect of the design process, the following question must be posed:

1. How can digital tools assist in the process of searching for a feasible solution under the required conditions?

This research includes the connection to the engineering discipline in order to provide better information for decision-making during the design process of a customisable product. The purpose is to guarantee that custom solutions developed according to design considerations fulfil structural requirements under operating conditions. This proposition is crucial to constructing a generative design system capable of creating feasible solutions that can proceed to the production system.

1.3.3. Production Process

A physical artefact can be summarised as the result of negotiation that includes design propositions, material possibilities and manufacturing constraints. Taking these premises into account, it is possible to characterise an approach as design-oriented when the design variables push manufacturing towards new realms in order to accommodate them. Conversely, a manufacturing-oriented approach considers the limitations of existing manufacturing processes in order to establish the constraints that influence the design output. This latter approach has been researched in mass customisation implementation studies using existing subtractive or additive processes as design drivers.

This thesis adopts a design-oriented approach. The requirements defined in the design language establish the principles that influence the development of the production system. The goal is to examine the following question:

1. How can an established design language cross-influence the development of production systems?

The thesis focuses on the development of forming production systems according to mass customisation requirements. It presents the principles for the development of a reconfigurable tooling system for the automated production of custom bentwood components.

1.3.4. Product Evolution and Process Iteration

Mass customisation requires the development of robust design methods that support flexible product development, guarantee product quality, and accommodate new iterations as part of the design process. Accordingly, this research aims to answer the following questions:

1. Can the proposed generative design system accommodate new iterations?
2. How can a design language evolve?

The research assesses an iteration of the generative design system by proposing the transformation of the design language.

1.4. Research Goals

Taking into account the principles and context described in the previous sections, this research aims to contribute towards improving designing for the mass customisation paradigm. The study focuses on methods, in order to contribute towards enhancing the patterns for collaboration throughout the product development process, from design to manufacturing. The goal is to provide designers and the industry with the ability to develop products and systems for customisation which serve the functional and symbolic needs of the final users.

The motivation for studying the furniture design industry is twofold. The first reason is the desire to have an impact on an important area of product design. Furniture design plays a crucial role in defining the domestic environment, where a significant part of peoples' lives takes place. Users therefore apply both utility and significance criteria to the acquisition process for this class of objects. The typology selected as a case study and framework for the research is the chair. A chair is a structure designed to support the human body, although its functionality is not confined to this primary aspect. In fact, chairs allow for the study of multiple aspects of design, such as aesthetics, ergonomics and construction principles, in addition to structural resistance.

The second motivation is related to the need to select an area and a typology with manageable variables that establish well-defined boundaries for the research. Furniture design, in particular, chair design, meets these requirements, thus enabling the researcher to identify the set of variables involved and study how their values may affect the design results, thereby establishing the envisaged mass customisation model.

In accordance with the two motivation principles stated above, a set of Thonet bentwood chairs was selected as the specific case study. Thonet chairs represent a technological and typological advance that has defined mass production as the standard industrial model in the furniture industry since the 19th century (Wilhide, 2010, p. 29). In addition, the production is highly manual, which provides scope for conceptualising the principles for an automated production system. As a result, Thonet chairs constitute a well-defined framework suitable for studying how the industrial model of mass production can evolve into mass customisation.

The theoretical model for the research is based on the customisation model devised by Duarte (2001), which addresses a design and a production system controlled by a computational system that supports both the exploration of solutions and the generation of data for CNC production. This research represents the first application of this model to the field of product design, and more specifically the furniture design industry.

The thesis proposes a generative design system, defines the basis for its iteration, and conceptualises a production system that responds to flexible design principles.

The generative design system encodes the procedures defined in the embodiment design phase, considering a conventional model of the design process. It comprises two complementary subsystems, namely shape generation and shape evaluation, each encompassing two parts. The first part of the shape generation subsystem addresses the question of translating tacit knowledge into explicit knowledge. It is accomplished by formalising the identity principles of the design style as a shape grammar. The shape grammar addresses both formal and functional design requirements, guiding the subsequent parts of the system. The second part of the shape generation subsystem is concerned with encoding explicit knowledge as digital representation.

The shape evaluation subsystem encodes the engineering variables into the generative design system. The computer is used to ensure that a custom design fits the performance requirements. Simulation is used to analyse each custom solution against performance requirements. In the event of failure, the optimisation searches for a feasible configuration in a large solution space, thus meeting the predefined goal.

One important premise of mass customisation models is their iterative principle, used to achieve the goal of continuous refinement of both the design criteria and design results. This study takes this premise into account by investigating a novel iteration of the generative design system. The thesis proposes a methodology to cope with the need to expand the outputs of the design language and refine digital information.

The goal of the generative design system is the production of custom solutions. The conceptualisation of the reconfigurable tooling system for wood bending therefore takes the specific conditions of the case study into account.

1.5. Contributions

The main novelty of the research presented in this thesis is the methodology for developing and using a generative design system that integrates information created in the fields of design and engineering during the design process, and enables it to be linked to a production system. It can be summarised as threefold.

Firstly, it proposes the use of shape grammars as the basis of a methodology to support the embodiment design phase of a furniture design process for mass customisation. Shape grammars are used to encode the rules of an existing design style, thus defining a design language. The term 'design style' refers to the set of formal and functional features shared by a set of designs, whereas 'design language' defines the set of designs generated by the shape grammar. The designer may explore alternative preliminary layouts by applying the rules and by varying their parameters to generate custom solutions. Alternative preliminary layouts may correspond to different topologies within the defined design language.

Secondly, it implements the shape grammar as a set of parametric design models, each permitting additional exploration of a fixed topology. The parametric design models are then linked to simulation and optimisation tools to ensure that the custom solutions generated are directly correlated with performance requirements under operating conditions. The generative design system is a device that enhances the designer's ability to define and explore the universe of preliminary layouts within a design language and supports the automatic search for definitive layouts.

Thirdly, it links the digital information to the production system. The first steps towards the development of a reconfigurable tooling system for wood bending are conceptualised on the basis of the specific characteristics of Thonet chairs.

The result is an integrated model for mass customisation in the furniture design industry.

The main contributions of this thesis are:

1. A methodology to develop a generative design system for mass customisation in the furniture industry. To achieve its intended goals, the envisaged system requires a frontend configurator and a production system. The thesis studies the generative design system, clarifying the formalisation process that allows for an appropriate degree of customisation of a design language, supports design decisions and generates information for the production system.
2. The definition of a customisable design language that includes design and engineering knowledge.

3. A shape grammar-based methodology to define and refine a generative design system.
4. A characterisation of the Thonet bentwood chair design style.
5. The outline for a reconfigurable tooling system for wood bending.

1.6. Thesis Structure

The thesis is organised into three main parts, excluding this introduction.

The first part focuses on the theoretical background and research methodology and comprises Chapters 2 and 3.

Chapter 2 addresses the theoretical background of the research and has six sections, besides a summary in the end of the chapter. The first section introduces the theoretical framework for mass customisation. It identifies the strategic and operational models that define the field, and how they influence the interaction between designers, consumers, and manufacturers. The second section reviews the state of the art in digital design. It explores the use of computers in the design process, detailing the generative design methods and the inclusion of engineering design variables in the design process. The third section discusses the importance of furniture design as an experimental field within product design. The fourth section reviews the state of the art in reconfigurable tooling systems, with a particular focus on those associated with wood bending. The fifth section presents the formulation of the hypothesis, and the sixth section introduces the theoretical model and describes how it is adapted to the specific conditions of this research.

Chapter 3 explains the methodology used in the research process. It characterises the research strategy and the research structure.

The second part analyses the knowledge developed by Thonet and describes the action research activities undertaken during the case study. It comprises Chapters 4, 5, 6 and 7.

Chapter 4 presents the empirical knowledge developed by Thonet, defining the corpus of designs used as a case study. The chapter is divided into four sections, besides a summary in the end of the chapter. It overviews the history of Thonet bentwood chairs, their design and production systems and influence on furniture design. In addition, it characterises the selected chairs that constitute the corpus.

Chapter 5 details the methodology used to develop the generative design system. The first section introduces the general structure of the system, the interconnection between the subsystems and its constituent parts. The second and third sections present the shape grammars and parametric design models which define the shape generation subsystem. The fourth and fifth sections detail the simulation and optimisation parts, which determine the shape evaluation subsystem. All these sections share a similar structure, which introduces the topic, details its development procedures and discusses the results. A summary overviewing the development of the generative design system concludes the chapter.

Chapter 6 explains the transformation of the generative design system. The first section outlines the goals of the transformation. The second and third sections present the transformation of the shape grammar and the parametric design models, respectively. The fourth section details the transformation of the shape evaluation subsystem, particularly of the optimisation part. Likewise the previous chapters, a summary concludes the chapter.

Chapter 7 describes the conceptualisation of the production system. It introduces the issue of developing reconfigurable tooling systems for mass customisation under the general category of forming production systems. The production concepts are presented according to the material and technical considerations defined by the case study, followed by a discussion of future developments for implementing the envisaged concepts, and a summary of the chapter.

The third part presents a synthesis of the research and comprises Chapters 8 and 9.

Chapter 8 summarises the results of the research and interprets them in terms of the initial goals. The results are discussed on three levels of analysis: the macro, meso and micro levels.

Chapter 9 concludes the research, presenting the contributions to knowledge and identifying paths for future research.

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2. State of the Art

2.1. Mass Customisation

This section defines the macro and meso levels of the theoretical framework for the research. Mass customisation (MC) comprises a set of modifications that have been changing the industrial system for the design, production, and acquisition of products and services in recent decades.

This section is organised into five subsections. First, it introduces the principles of the post-industrial society to characterise the new paradigm. Secondly, it details the fundamental principles of mass customisation, then it discusses how these principles have been implemented, with a particular focus on the furniture design industry. The fourth subsection discusses the role of the consumer in the customisation process. The section concludes with a review of the changing roles of designers, manufacturers and consumers, and the possibilities that have emerged regarding the extent of the transformations that characterise the state of the art.

2.1.1. Introduction

"Analytically, society can be divided into three parts: the social structure, the polity, and the culture. The social structure comprises the economy, technology, and the occupational system. The polity regulates the distribution of power and adjudicates the conflicting claims and demands of individuals and groups. The culture is the realm of expressive symbolism and meanings. It is useful to divide society in this way because each aspect is ruled by a different axial principle. In modern Western society the axial principle of the social structure is economizing – a way of allocating resources according to principles of least cost, substitutability, optimization, maximization, and the like. The axial principle of the modern polity is participation, sometimes mobilized or controlled, sometimes demanded from below. The axial principle of the culture is the desire for the fulfilment and enhancement of the self. In the past, these three areas were linked by a common value system (...). But in our times there has been an increasing disjunction of the three and (...) this will widen" (Bell, 1999, p. 99).

Daniel Bell (1999) coined the term 'post-industrial society' in 1973 to characterise a series of changes that were occurring throughout the structure of society and differed from those of pre-industrial and industrial society. The author specified technological innovation as the most crucial factor responsible for the ongoing transformation of society's structure. The extent of the transformations that began to occur during the second half of the 20th century can be summarised as follows: the gradual replacement of an economy based on commodity production by a service-based economy; an increasing demand for professional specialisation; the process of adopting innovation supported by theoretical knowledge; technological advances dependent on the codification of theoretical knowledge in intelligent systems; and communication infrastructures which have evolved into aggregation factors.

The concept of post-industrial society encompassed the disaggregation of society's constituent elements at different times and rates. According to this premise, each change triggers a chain of interactions with the existing realities, which means that there are several possibilities for accommodating innovation and continuously refining procedures. As a consequence, one of the most significant problems of post-industrial society is accommodating different types of knowledge within coherent models.

Considering a similar paradigm but with a particular interest in envisaging future scenarios, Alvin Toffler (1970, 1989) forecast the impact of technological development as accelerator of change across the structure of society. He explored the social consequences of such transformations through a systematic examination of the cultural, economic and individual perspectives.

Regarding the product design domain, the author proposed that once manufacturing capabilities could meet consumers' basic needs, the next step would be to offer diversity. This would be supported by the increasing use of automation in the production process, which would lower the cost of providing variation. In terms of consumer relations, the principle that they are an heterogeneous group (Smith, 1956) would lead to increased customisation. Moreover, consumers would start to play active roles in the design process in order to fulfil their "personal needs for beauty, prestige, individualization, and sensory delight" (Toffler, 1970, p. 224). These transformations represent a change from commodity manufacturing into service-based production (Toffler, 1970, p. 453). The continuous developments would lead to "the greatest variety of unstandardized goods and services any society has ever seen. We are moving not toward a further extension of material standardization, but toward its dialectical negation. The end of standardization is already in sight" (Toffler, 1970, p. 265).

Although variety and shorter life-cycles lead to the end of standardisation, they still can be interpreted as company-based approaches. Toffler further extended this argument in *The Third Wave* (1989 [1980]) by analysing how automation and modularity would allow for greater flexibility of production, thus enabling customisation. Moreover, companies would continue to lower their operating costs through service-based approaches in which consumers would perform tasks previously carried out by the company.

Accordingly, the author presented parallel changes in consumer patterns, using the term 'prosumer'. In addition to individualised choices and service-mediated relations with companies, the consumer would increase its involvement into the production process and would then explore the possibility of establishing bottom-up approaches.

The above-mentioned principles are the basis of the concept of mass customisation (Davis, 1987).

2.1.2. Definition

"The consumers use the software to create the final application, and hence products themselves. Similarly, computer-aided design lets the customers design their own specifications" (Davis, 1987, p. 55).

New relations between consumer and producer form the basis of Davis' concept of mass customisation (1987, p. 140), which merges "the production and distribution of customized goods and services on a mass basis."

The application of technology is envisaged as the core of the industrial model, providing economic feasibility and speed to meet customer specifications. Davis also argued that companies had to evolve from pyramidal organisations into network organisations able to reduce concept-to-product time, work more closely with consumers and increase specialisation and integration (Davis, 1987, p. 79).

The term itself comprises two opposite terms: 'mass' and 'customisation'. 'Mass' often referred to mass production, an industrial model characterised by the high volume production of standardised products. Efficient long-run production cycles were targeted at a large, stable and homogeneous marketplace. 'Customisation' was often associated with tailored products made according to the specific needs of a customer, involving low volume production techniques.

Pine (1993) systematised Davis' concept as a holistic management theory that combines these two apparently contradictory concepts. According to Pine, mass customisation represents a break with the traditional methods of mass production and standardisation, thus establishing itself as a new paradigmatic industrial model. Flexible and responsive strategies enable the efficiency of mass production to be combined with the ability to customise products according to end-user specifications. The transition to mass customisation copes with market turbulence, which is characterised by the instability and unpredictability of demand, changes in economic cycles, high levels of market saturation and shorter life cycles (1993, p. 56).

Both Davis' concept and Pine's systematisation share similar underlying principles for mass customisation: a different organisational structure for companies, responsive processes to meet individual needs, and a customer-centric approach enabled by technology.

Information technologies and flexible production processes are the core of mass customisation. According to Pine (1993, p. 48–49) the use of computer-numerical control permit companies to establish systems capable of: improving the relation between design specification and manufacturing; producing customised parts; and responding to change in demand.

Technology is applied to optimise and link the processes of design, production (Kotha et al., 1993), marketing and delivery of products and services (Pine, 1993, p. 173). Pine (1993) argues that MC principles may be applied in different degrees during the establishment of the referred processes, thereby offering several possible models for MC. Continuous improvement allows for the possibility of producing at a pace comparable to industrial production (Tseng & Jiao, 2001). Moreover, as different products are produced using the same production systems, companies achieve economies of scope (Panzar & Willig, 1981) rather than economies of scale as with mass production. The goal is to explore niche markets and grow.

MC strategies focus on customer needs and aim to establish a closer relationship with them. Hart (1995, p. 40) indicates that understanding customers' desires and unmet needs constitute the 'customer sensitivity' that companies must pursue in defining requirements for product development. Consumers are able to participate in the production cycle with different levels of customisation. A higher degree of customisation occurs when the consumer participates in both the design and the fabrication processes, and a lower degree when participating in the assembly and the distribution processes (Gilmore & Pine, 1997; Duray et al., 2000). The consumer experience becomes a service and the market becomes increasingly segmented, progressing towards greater degree of customisation.

2.1.2.1. The Transition from Mass Production

Pine et al. (2000 [1993]) distinguished mass customisation from mass production (MP) and lean production (LP). Compared with mass production, whose main focus is production efficiency, the primary focus of MC is on the customer. The authors classify lean production as the continuous improvement of mass production and a subset of mass customisation. Although lean production employs multi-skilled workers at all levels and automated machines to produce variety (Womack et al., 1990), the authors argue that it lacks an "efficient linkage system" (Pine et al., 2000, p. 151) and greater autonomy. MC also encompasses the possibility of consumers participating at different processes of the production cycle (Duray et al., 2000), whereas lean production only provides selection in the assembly process.

Lampel and Mintzberg (1996) analysed MC as an evolution of mass production. Their analysis contemplates the existence of multiple approaches that can be categorised within five strategies. These strategies comprise the separate properties of the different processes of the production cycle, which encompasses the design, fabrication, assembly, and distribution of a manufactured product. The authors classify customisation as a bottom-up strategy in the production cycle, whereas it is a top-down strategy in standardisation. Their five strategies can be summarised as follows:

1. 'Pure standardisation'. This is the prevailing strategy in MP. A unique design is optimised for standard production and an automated assembly line works in long-run cycles to achieve high volume production. The strategy targets a large and uniform stable marketplace. Consumers are perceived as a homogeneous group and do not influence the design of the product, nor its fabrication, assembly, and distribution.

2. 'Segmented standardisation'. This involves processes similar to MP, with gradual market sensitivity. The market is analysed as large homogeneous groups that can be segmented (Smith, 1956). The goal of segmentation is to anticipate user needs as a requirement for product development. Products are often standard mass produced designs with subtle

variations. Consumers are offered greater variety but do not actively participate in the production cycle.

3. ‘Customised standardisation’. This is the prevailing strategy in LP. The production process is standardised but the assembly and distribution processes are customised. The design process is centred on a common design envelope with modular components (Ulrich & Tung, 1991). This principle allows components to be interchanged between designs, resulting in multiple combinations. Modularity enables consumers to become involved in the production cycle by configuring the available options during the assembly process.

4. ‘Tailored customisation’. Companies produce a prototype design which accommodates a certain degree of variation. Consumers participate in the design process to suit their particular needs, but do not change the main design. Therefore, the make-to-order (MTO) production strategy is implemented to support the customisation of the fabrication process.

5. ‘Pure customisation’. The future user and the designer collaborate from the start of the design process. Accordingly, all the processes in the production cycle are customised. Nevertheless, this is considered a personalisation approach, because it lacks the efficiency in terms of time and cost to become viable on a larger scale (a mass customisation requirement.)

Kotha (1996) researched the implementation of MC strategies in a company that mass produced bicycles. His study demonstrated that these strategies can work simultaneously, with MC starting as a separate business unit to serve different market segments.

The factory used a centralised design process and rotated teams in the MP and MC business units. Therefore, information from both business units and their respective market segments continually promoted the refinement of its processes. Moreover, the product designers analysed ideas from customised designs co-created with users and optimised them for MP. Customisation functioned as both a business and a trend assessment tool.

Kotha concluded that human resources, advanced technologies and a close supplier network were equally important for MC implementation. Moreover, he determined that continuous improvement was possible only because the company had developed manufacturing tools and software (customised flexible manufacturing systems) that were particularly suited to their needs.

2.1.2.2. Evolution

“The corporation that is now emerging is being designed around a skeleton: information, both the corporation’s new integrating system and its articulation” (Tapscott, 1995, p. 85).

The first decade of MC systematisation (1993-2003) comprised two major approaches: analytical and prescriptive. The former addresses strategic management issues, departing from Pine’s definition to focus on the ‘what’ and ‘why’ of mass customisation (e.g. Hart, 1995; Lampel and

Mintzberg, 1996; Pine and Gilmore, 1997; Zipkin, 2001). As McCarthy recalls (2004, p. 349), there are a large amount of conceptual models which characterise generic approaches to mass customisation or particularise certain aspects. Prescriptive studies consider operational issues. They focus on the 'how' of MC, reviewing implementations and proposing models and specific procedures across the production cycle for enabling mass customisation (e.g. Kotha, 1996; Swamidass & Kotha, 1998; Duray et al., 2000).

Within the wide range of studies, the definition of mass customisation is a relatively fixed concept that relies on the evolution of organisational structure from a pyramidal to a network organisation (Tapscott, 1995, p. 82). Companies evolve from production-focused to customer-centric companies (Tseng & Piller, 2003) that integrate customers into the production cycle. The production, exchange and management of information becomes a crucial asset for the implementation of mass customisation strategies (Piller, 2002).

In a review of the first decade of mass customisation literature (Da Silveira et al., 2001), the authors refer to the lack of studies on practical implementations. The same authors (Fogliatto et al., 2012) thoroughly reviewed the second decade of MC studies. Even though this thesis does not consider exactly the same decade division (opting instead for 2004-2014 and Fogliato et al. 2002-2012), the major developments in the field are inferred on the basis of their analysis.

According to Fogliatto et al. (2012, p. 15) the development of mass customisation in the second decade is supported by the implementation and use of web-based configurators and research in new manufacturing processes. Accordingly, companies have been refining their processes to provide a closer and customised service for users. The widespread adoption of the internet and mobile devices has determined new patterns of behaviour, both in consumers and companies. Considering these changes, Salvador et al. (2009, p.71) proposed a new definition of mass customisation, which characterises it as a dynamic process of continuous transformation that companies must pursue in fulfilling the consumers' needs. According to the authors, achieving mass customisation requires a company to embody the mentioned principles into its strategy and operations, and evolve over time into a more refined industrial model.

The authors identify three capacities required to implement mass customisation: solution space development, robust processes, and choice navigation. 'Solution space development' requires product definition and an assessment of the customisation space, by customer validation. They propose user innovation toolkits (a translation of Von Hippel's B2B model to the B2C segment) to acquire information directly from consumers. The data is analysed and becomes the requirements for new product development. 'Robust processes' relates to the above-mentioned virtual enterprise and initial definitions comprising FMS, modularity, and information integration. Finally, 'choice navigation' is the support system aimed at minimising customer choice during the elicitation process.

Several factors influence MC implementation varying according to company culture and context, in particular product complexity, the degree of customer involvement in the production cycle, the solution space, and the production process (McCarthy, 2004).

2.1.3. Implementation

According to the theoretical models presented in the previous subsections, MC strategies require changes in organisational principles and processes. The design, fabrication, assembly, distribution and marketing of products must offer a quicker response, greater efficiency, and a closer relationship with consumers. Information technologies and flexible manufacturing systems are resources that support the implementation of mass customisation. However, from a prescriptive perspective, modularity is the key aspect that enables the strategy to be implemented.

By employing modularity companies are able to combine production efficiency with variety. The standard modules are produced in higher volume and the custom modules are produced in lower volume. The combination guarantee a certain degree of flexibility for companies, in terms of time and cost, whilst enabling customisation for customers (Huang, 2000, p. 149).

Duray et al. (2000) developed a conceptual model for mass customisation which categorised companies from the perspective of operations. The authors considered two key variables in their model: the level in the production cycle where the customer could specify product characteristics, and the type of modularity used for the product. Modularity is the enabling strategy adopted to implement MC, since it provides companies with the ability to integrate both external and internal factors into the product development process. External factors such as market turbulence, increased competition, demand for lower prices, differentiation and customisation lead to refinement of internal processes. Internal processes must cope with the apparently contradictory issues of high volume production ('mass') and different product versions ('customisation').

This subsection presents the concept of modularity and its application in the product development process, from design to manufacturing. After introducing product architecture and defining product modularity, modular products are classified according to their application in MC. The goal is to cross-reference the types of modularity with the particular strategy and respective customer involvement. Product family architecture is then characterised as a support methodology for developing product versions and the way in which product models are connected in the product development process. Following this, the application of modularity in planning the activities in the product development process and in defining the production process is presented. The subsection ends with a review of the implementation of mass customisation in the furniture design industry.

2.1.3.1. Modularity

"Product architecture is the scheme by which the function of a product is allocated to physical components" (Ulrich, 1995, p. 419).

Product architecture is the result of product design activity and coordinates coherence between versions of a product and families of products. Its definition is crucial to the overall performance of the company, since decisions are linked to manufacturing capabilities, R&D issues and managerial issues. The establishment of a product architecture requires the definition of the functionality of the overall product and of each component, and the specification of the interfaces between all components (Ulrich, 1995, p. 420).

Product architecture comprises two possible typologies (Figure 2): integral and modular. In integral architecture all component interfaces are coupled. In modular architecture, the component interfaces are de-coupled, which means they can perform independent functions. According to Ulrich (1995, p. 424) there is no total modularity, but rather degrees of modularity within a product. The degree of modularity may vary according to the level in which the product is analysed, namely at the assembly level or at the individual component level.

Figure 2. Product architecture: a) Integral; b) Modular.
(Source: a) IKEA, 2014; b) Shick, 2014).

Name	Kallax
Designer	Tord Björklund
Manufacturer	Ikea, Sweden (2013)
Materials	Chipboard, MDF
Size (mm)	height 770, width 770, depth 390

Name	Airsquare
Designer	Oliver Shick (1969-)
Manufacturer	Self-production (2001)
Materials	Expanded polypropylene (EPP)
Size (mm)	height 390, width 390, depth 300

Figure 2 illustrates two product architecture typologies for a similar design. Figure 2a) shows an integral architecture in which four shelving function locations are optimised in a single object. Figure 2b) presents a modular architecture in which each module performs a single shelving function. Integral architecture promotes better product performance, since mass and weight are reduced (Ulrich & Tung, 1991) in comparison to modular architecture. The disadvantage is that in case of product redesign, a change to one single component may also require changes in several related components. Modules allow changes to be made to a few isolated functional elements of a product without necessarily affecting the design of other elements (Huang, 2000, p. 150).

Modular architecture requires well-defined interfaces which allow for interaction between modules. The dynamic combination of modules results in different product configurations (or versions). From the producer's perspective, redesigning or adding modules becomes more feasible since it may not affect the redesign of related components and customers are given the opportunity to select a configuration according to their particular needs. Modular product architecture therefore enables high volume production to be combined with customisation.

Ulrich (1995, p. 424) distinguished three sub-types of modular architectures, according to their interfaces: slot, bus and sectional. In a slot architecture each function comprises a dedicated type of interface. Therefore each interface accommodates a specific type of modular component. A bus architecture encompasses a central component sharing a common interface to which different modular components can be attached. In sectional architecture there is no central component of the product. Rather, each module shares the same type of interface and can be connected to each other interchangeably.

Modularity encompasses independent and interchangeable components that generate product versions. In order to achieve modularity, the product architecture must provide interfaces that allow for the interchange of components.

Modularity is a relative property of products, which may have a higher or a lower degree of modularity (Ulrich & Tung, 1991). The flexibility of modular products relies on the interaction between different components. The combination of standard and custom components enables companies to mass-produce the more required components, which results in economies of scale and a wider range of products.

According to Ulrich and Tung (1991, p. 77–78) there are five types of modularity (Figure 3). Component-swapping modularity is employed when companies aim to create different versions of a product to enable a degree of choice to consumers. Different components can be attached to the same generic product thus creating different versions. In component-sharing modularity the same standard component is mass-produced and it is used across different product families. Fabricate-to-fit modularity is employed when a company is able to use a standard component across different products by varying its dimensions. It enables the creation of variants of a product. In bus modularity product versions are created by assembling different sets of components to the same basic product. In sectional modularity the product may comprise several configurations, by assembling different sets of components which share the same interface.

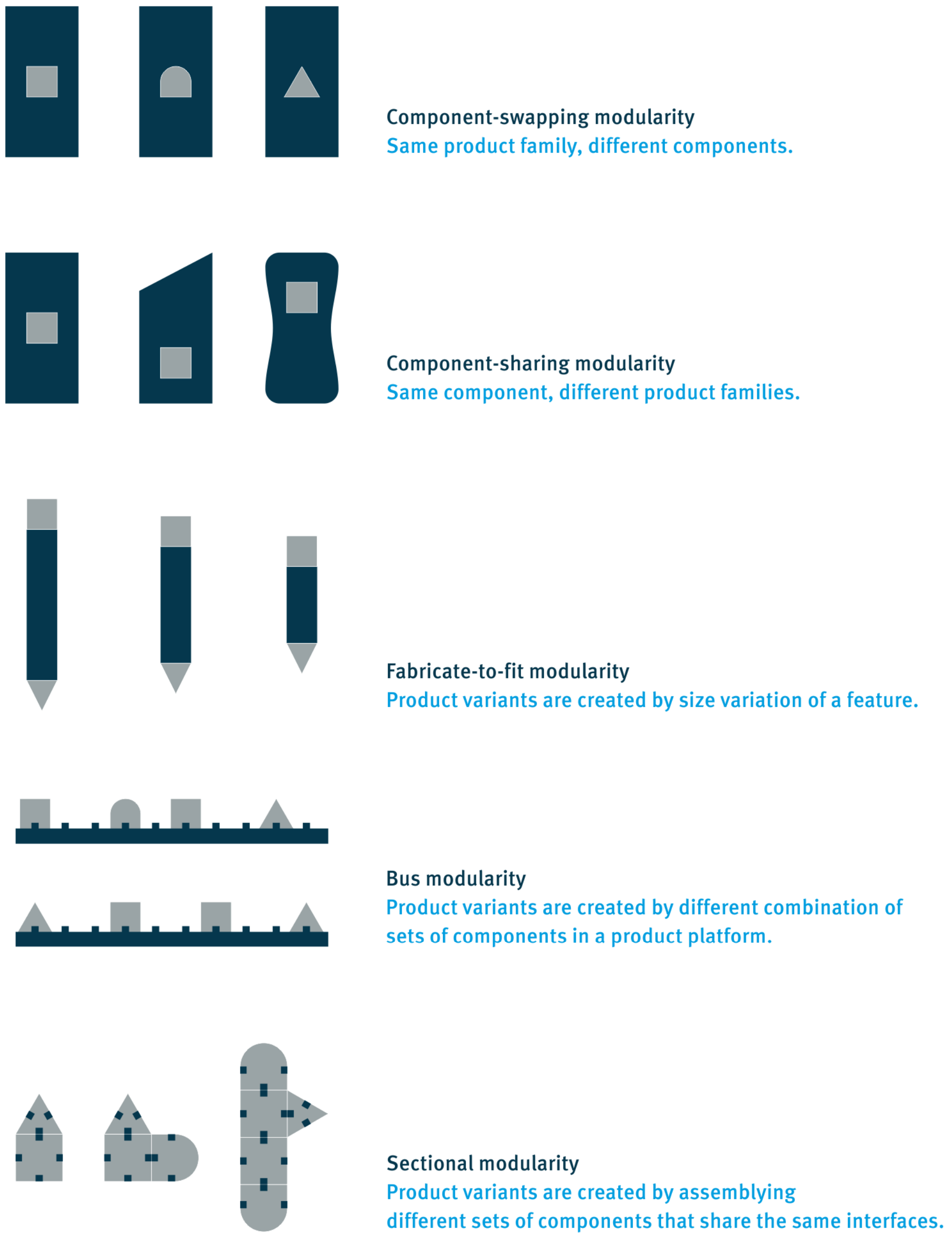

Figure 3. Types of modularity (adapted from Ulrich & Tung, 1991, p. 77)

2.1.3.2. Modularity in Mass Customisation

Duray (1997) analysed the five types of modularity in terms of customer involvement in the production cycle and the MC strategy employed by the company. Figure 4 illustrates an adaptation of Duray's model. The model superimposes Ulrich and Tung's classification of modularity onto Lampel and Mintzberg's model. It shows how consumers, strategies and modularity are organised in different approaches to MC.

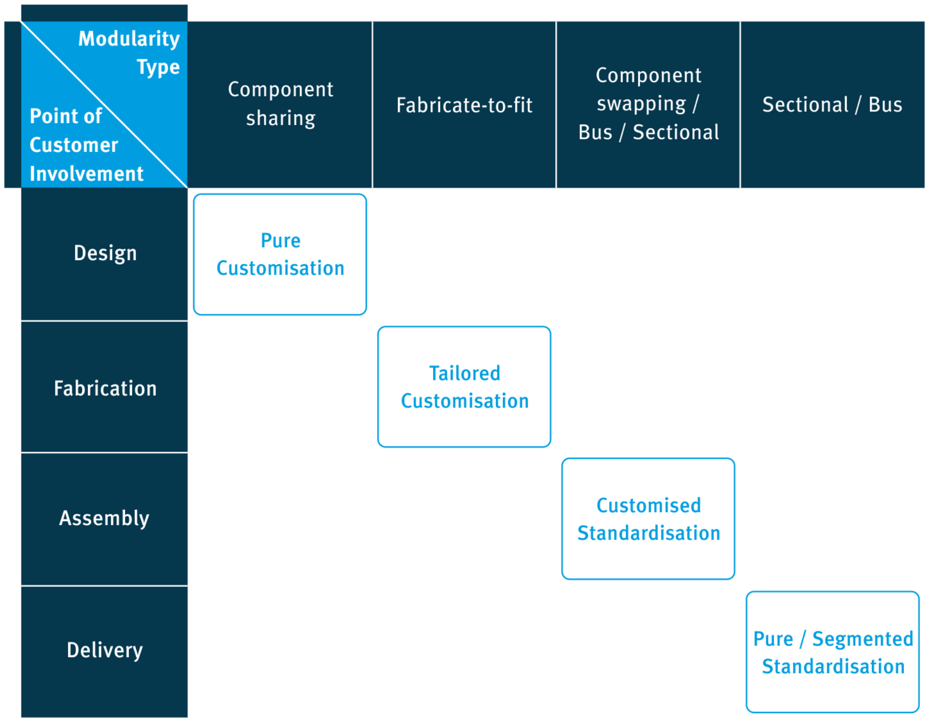

Figure 4. Use of modularity in mass customisation (adapted from Duray, 1997, p. 48)

In 'pure customisation' there is high customer involvement in the specification of the product, and collaboration with the producer begins in the design process. Designs based on component-sharing modularity enables companies to decrease costs. Standard components are made-to-stock (MTS) and are employed in the design of different products.

In 'tailored customisation' the producers design a prototype of the product and then use make-to-order production strategies to tailor the product to the customer's needs. Fabricate-to-fit modularity enables the dimensions of a module to be altered before they are combined with other components, thus ensuring a quick response. This customisation strategy therefore relies on the use of flexible manufacturing systems and computer-integrated manufacturing (CIM) to achieve proper flexibility.

Zipkin (2001) analysed how tailored customisation could be introduced into the fabrication process. The author identified a direct correspondence between the level of difficulty in implementation and the number of spatial dimensions of the object. Accordingly, customisation addressing one dimension of the product is easier to implement than in two dimensions which, in turn, is easier to implement than customisation in three dimensions. One-dimensional customisation requires cutting a particular component and is often related to width, length, or height adjustment (e.g. the cut of a rod in a bicycle or golf club to suit consumer needs). Customisation in two dimensions uses laser-cutting, printing or CNC routing to tailor shape properties (e.g. tailoring a fabric, printing a photo on a mug or customising table top dimensions). Zipkin considered three-dimensional customisation as harder to implement and more expensive. The author estimated that customisation of moulds (forming production processes) would not happen in the near future.

In 'customised standardisation' customer involvement occurs in the assembly process (ATO). Component-swapping, bus and sectional modularity enable consumers to customise the product based on the possible predefined configurations designed by the company. The final configuration is the result of the interchangeability of components.

In 'pure / segmented standardisation' MTS production strategies are employed to reduce production costs. As in standardised customisation, the product architecture is modular. The difference is that customers are not involved in the production cycle, although Duray classifies it as delivery customisation. In this strategy, modularity is a characteristic of the product architecture and allows the customer to customise the product after acquisition. Modular shelving systems that allow users to buy additional shelves, or living room systems that permit different configurations are examples of this strategy.

2.1.3.3. Product Family Architecture for Mass Customisation

The implementation of mass customisation requires the ability to accomplish several goals simultaneously, which can be summarised as providing variety by means of efficient and quick responsive processes. To fulfil these goals companies must develop an integrative methodology that supports the different aspects of the product development process and of the established product platform (Tseng & Jiao, 1998, p. 12).

The term 'product family architecture' (PFA) (Tseng & Jiao, 1998) is used to designate similar terms in the MC implementation context. It also designates the 'product platform' and extends Ulrich's concept of 'product architecture' (1995), combining it with the concept of 'architecture for product families' developed by Erens & Verhulst (1997).

Product family architecture evolved from the arrangement of functional elements, mapping of functional elements to physical components, and specification of interfaces (Ulrich, 1995) to comprise the different domains of abstraction corresponding to company departments. It is therefore an integrative methodology that improves communication and consistency in different aspects of the product life cycle (Jiao & Tseng, 1999), thus enabling MC to be implemented. The product development process from idea to market became centred on PFA.

Its rationale enables product versions and variants to be designed from a basic product design, rather than by designing individual products. The definition of integral components, modular components and the interfaces between them stabilises the product development process. Its application allows for the simultaneous development of components by different teams or outsourcing companies, and ensures the reuse of information to redesign future product versions.

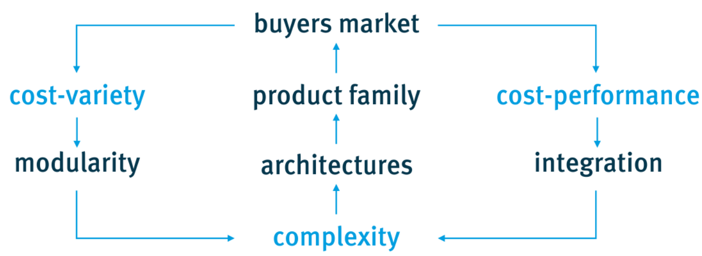

Figure 5. Architecture for product families (adapted from Erens & Verhulst, 1997, p. 66)

Figure 5 shows architecture for product families as an integrated methodology that addresses the complexity of cost-performance and cost-variety variables that exist in MC. Customers demand variety, customisation and reduced costs. These issues, combined with contemporary market features such as increased competition and shorter product life cycles, require new methods to cope with complexity. From the perspective of the producer, cost-performance, variety, and quick response are issues to consider when implementing a product development process. According to Erens and Verhulst (1997, p. 165) integrating the stable aspects of the envisaged product family improves the cost-performance trade-off, while employing modular strategies improves the cost-variety trade-off.

According to Tseng and Jiao (1998, p. 15) PFA is the methodology that companies use to develop the basic 'commonality', which is embodied in the product family, or the generic layout, that can be customised by end-users. Besides enabling the definition of the product family, the PFA encoded knowledge becomes the established base to support the future development of new products.

Product family architecture deals with the aforementioned issues, by breaking down the information into different departments of the company, therefore reducing the overall process complexity. Erens and Verhulst (1997) characterise the product family architecture as being constituted by three complementary models which establish the design and production processes, from requirements to conceptualisation, and from embodiment to production and distribution: the functional, the technological and the physical. These complementary models can be analysed as complementary descriptions corresponding to different views of the product by specialised disciplines. The goal is to develop the information in a coherent manner and establish the precise interdependences, thereby facilitating the exchange of information between the different disciplines involved in the product development process.

The functional model specifies the functionality of the product and serves as an assessment criteria for the remaining phases of the product development process. It results from the outlined strategy, the assessment of the business environment and the analysis of users' needs.

The technological model characterises the application of technology in the product's features. This definition relates with the product manufacturing but does not necessarily specifies how the product is made. The main focus is on clarifying the embodied characteristics of the product and how they address the required functions.

The physical model specifies the aspects related with the physical construction of the product. It relates directly with the development and implementation of the issues related with the manufacturing, assembly and logistics required to take the product to the market.

Jiao and Tseng (1999) interpreted the three-model approach as the methodology for rationalising product development for MC and related each model to its corresponding business function. The functional model is produced by the Sales and Marketing department, which translates customers' needs into functional requirements. The technological model is the design process created by the Design and Product Development department. It translates functional requirements into design parameters, thereby structuring the modular architecture of the product and the combination of the modules. The physical model is the production process developed by the Manufacturing and Logistics department. It translates design parameters into physical components and assemblies operations, assessing the available production capabilities and studying effective economies of scale. The three models become an iterative methodology within which different aspects of the product can be accommodated.

Each model comprises a different level of abstraction (Erens & Verhulst, 1997). This means that there is a progressive formalisation of the product development process which is consistent with the product description. The goal is to break down complexity and establish interdependencies, therefore allowing for a multidisciplinary approach to the process, which also facilitates validation of the product.

The authors listed four activities to describe the design cycle within the three models. The design cycle ensures that relationships are maintained between models and provides a means of validating and further developing the product:

1. 'Allocation' creates relationships between elements of the different models, i.e. functions are allocated to technology modules, which are, in turn, allocated to physical components.

2. 'Decomposition' adds detail to a specific model. Although the product description remains the same, each model decomposes the description to ensure specialised detailing of the product.

3. 'Composition' combines elements within a product model. It promotes collaboration between teams in different models in order to determine the particular features of a product.

4. 'Validation' assesses the quality of the product by relating descriptions made in different models.

Product family architecture responds both to flexibility and stability, rationalising the product development process for implementing MC. It promotes a trade-off between the number of functions and the number of components, and allows informed decisions to be made concerning the degree of customisation. These decisions combine an assessment of commercial viability with development, manufacturing and service (Erens & Verhulst, 1997, p. 174).

Depending on the complexity of the product, the robustness of information and the time investment mean that companies become organised around a specific product family architecture. One advantage of this is that previous information streamlines product redesign. However, according to Ulrich (1995), innovation requires new product family architecture.

Design knowledge and communication are key features of a product family architecture. An increasing amount of information is available across the production cycle and also more specialisation (Eppinger et al., 1994). Interdependencies in information encourage collaboration between different disciplines. Nevertheless, a multidisciplinary approach may evolve into an interdisciplinary approach if one discipline extends its conventional domain to other disciplines (Jiao & Tseng, 1999).

2.1.3.4. Process Modularity

"Just as modularity in design boosts innovation in products by freeing designers to experiment, so managers can speed up development cycles for individual modules by splitting the work among independent teams, each pursuing a different submodule of a different path to improvement" (Baldwin & Clark, 2000, p. 49).

Process modularity has strong links with component modularity and product modularity (Kusiak, 2002). Increasing specialisation in the product development process has raised managerial issues in terms of promoting coordination, flexibility, and concurrency of operations. Process modularity involves decomposition of the product development process into subsystems that both work independently and together as a whole (Baldwin & Clark, 2000).

Defining interfaces in a modular product enables design activities to be decoupled from production activities. Decoupling reduces complexity and allows parallel activities to take place, which can speed up the design process (Ulrich, 1994, p. 224).

Eppinger et al. (1994) studied the extension of this principle and concluded that too much decoupling of tasks lowers design quality. Therefore, a correct planning of the tasks and the mapping of the hierarchical and non-hierarchical nature of specific tasks enable to define a proper degree of tasks' integration. Reducing time and improving design quality are two variables that must be assessed in order to establish which tasks can be performed in parallel. The authors affirm that collaboration between design and manufacturing in the early stages of the product development process results in higher quality products. Production expertise develops multiple perspectives on product design, which leads to process iteration and quicker revision. This results in designs that are simpler to manufacture and less reworking at the end of the process. They concluded that the use of CAD tools, automation tools, and better channels of communication improved the product development process.

2.1.3.5. Production

The possibility of customisation poses challenges for mass customisation manufacturing since customer orders and the features to be customised are unpredictable (Qiao et al., 2006). Although manufacturing capabilities change according to the industry and product specifications, advances in CAD-CAM, product data management and the internet enable MC to be implemented (Tapscott, 1995; Da Silveira et al., 2001; Da Silveira & Fogliatto, 2005). Combined with FMS, they represent a group of technologies that facilitate the process of producing customised products in smaller quantities, but with greater variety (Swamidass & Kotha, 1998, p. 30).

Customer involvement in the design process leads to customisation of the manufacturing process (Qiao et al., 2006). The authors identified four challenges that the MC manufacturing system should respond to: a) providing greater flexibility than traditional FMS, since there is a greater variety of produced components; b) quick production planning and resource allocation to deal with the unpredictability of customer orders; c) modularising methods based on functionality rather than on the product; d) dynamic network control rather than the centralised and hierarchical control of traditional FMS. Dynamic network control should provide for the instantaneous exchange of information between functional modules in terms of production, suppliers, services and customised orders.

The authors simulated a modularised production line platform based on movable and re-configurable workbenches. Modularisation permitted customisation of operations and scale reconfiguration. The findings were confirmed in industrial applications in the auto industry (Salvador et al., 2009).

2.1.3.6. The Furniture Design Industry

Skjelstad et al. (2005) summarised Lampel and Mintzberg's model in four strategies, by merging pure standardisation and segmented standardisation under the same strategy of contemporary MP practice (Figure 6). They used the model to characterise the Norwegian furniture industry and to study the steps in the transition from one strategy to another. Based on the principle that customised standardisation and tailored customisation were the two main MC strategies, they analysed how transition could be achieved. Transition from pure standardisation to customised standardisation was studied in the case of an office chair manufacturer. The transition from pure customisation to tailored customisation was studied in a wooden staircase manufacturer.

In customised standardisation, products become flexible as a system of interchangeable components. Customers participate by selecting from a list of options and predefined elements. When the configuration process is concluded, the product is assembled and then delivered.

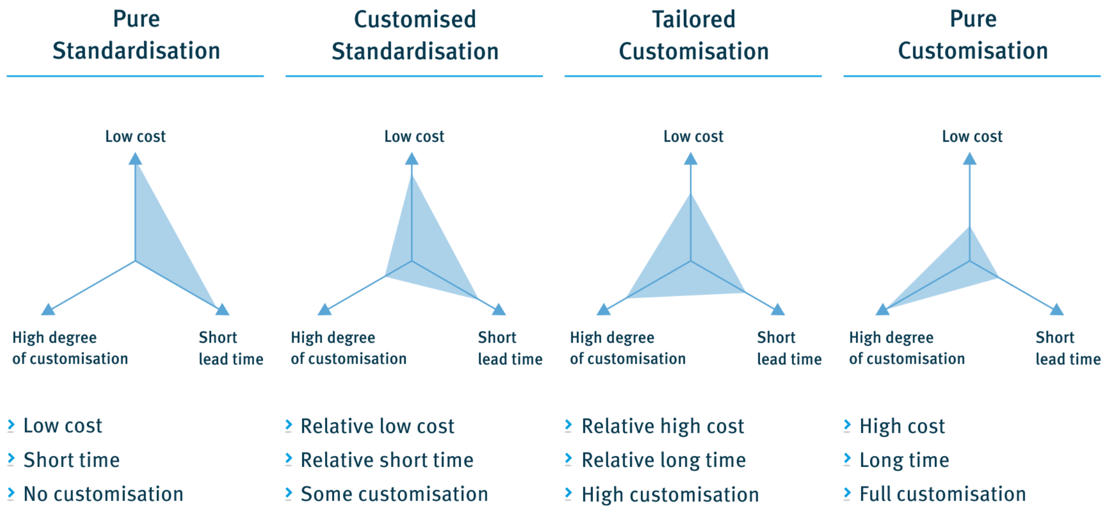

Figure 6. Mass customisation manufacturing demands (adapted from Skjelstad et al., 2005, p.1568)

The transition from pure standardisation to customised standardisation comprised the following changes: assembling products according to orders, to decrease stock volume (MTS to ATO); expanding variants of the modules that were more popular with customers and reducing those that were less popular; just-in-time (JIT) integration with suppliers; integration of information technologies (IT) with retailers and suppliers; division of material flow operations in the factory to deal more efficiently with variations in orders.

In the transition from pure customisation to tailored customisation, they observed that the company invested in CNC and an automatic painting line (FMS) to increase productivity and reliability, established dedicated production lines for each component family and individualised production schedules for each component, and implemented a web-based configurator to enable customers to design the product according to their needs.

In tailored customisation, product modularity is applied in production control and pre-defined design elements, such as connections between parts. Users participate in the definition of the final design by using online configurators, thus collaborating directly with the producer. When the configuration process is concluded, the product is fabricated on demand, rather than assembled, and then delivered.

The results confirmed the theoretical premises that information technologies, FMS and closer contact with users support MC implementation in the furniture industry. They also confirmed the proposition of Duray et al. (2000) that MC can only be achieved through product modularity and customer involvement.

Other studies confirm the success of the application of MC strategies in the furniture industry. Nevertheless, the implementation of the strategy must be assessed in accordance with the type of furniture sector and the capabilities of the company (Lihra et al., 2008; Qian & Deserti, 2009;

Dimkow, 2012). Distribution networks, sales channels, manufacturing capabilities and customer relations must be assessed in the implementation of a proper strategy.

2.1.3.6.1. The C-Moebel Project

The C-Moebel (C-furniture) research project was established in Germany in 1995. The protocol between HfB Offenbach and ten carpentry workshops equipped with CNC technology aimed to study MC from a design perspective. According to Gros (2001), the goals can be summarised as the development of CNC optimised techniques for furniture design and the implementation of the decentralised production of customised products.

Regarding the first goal, the research focused on studying digital wood joints, engraving and folding techniques as construction principles for CNC optimised furniture (Steffen & Gros, 2003). The goal was to test a vocabulary that permitted customised production of furniture.

Digital wood joints were a partial result of a study that analysed traditional European and Japanese wood joints, and optimised them so that they could be produced in one single type of operation on a three-axis milling machine. The project solved the limitation of the round corners left by the passage of the tool and extended the set of joints to methods that enable furniture parts to be assembled without resorting to fasteners. The output was disseminated as an open source project containing a set of fifty digital wood joints (Flexible Stream, 2013) in two-dimensional and three-dimensional digital compliant formats. A comprehensive set of instructions and furniture examples completed the documentation.

The development of furniture with digital wood joints represented the practical application of the semantic element in different furniture types. The result was a set of stools, shelves and desks (Gros, 2001) derived from box-like shapes, thereby guaranteeing customisation of dimensions in the Cartesian coordinate system.

The second set of experiments (Gros, 2003) involved experimenting with freeform shapes that could be cut from flat boards and studying origami principles to create three-dimensional shapes using folding techniques. The construction principle was established by cutting V-shaped grooves. In addition, the redefinition of ornamentation was studied using CNC image and typography engraving. The goal was to construct a digital pattern book that could be manipulated by producers and users to design the final customised item of furniture.

These construction principles were part of a larger project that aimed to implement a model for mass customisation based on digital design: the virtual production scenario (Figure 7).

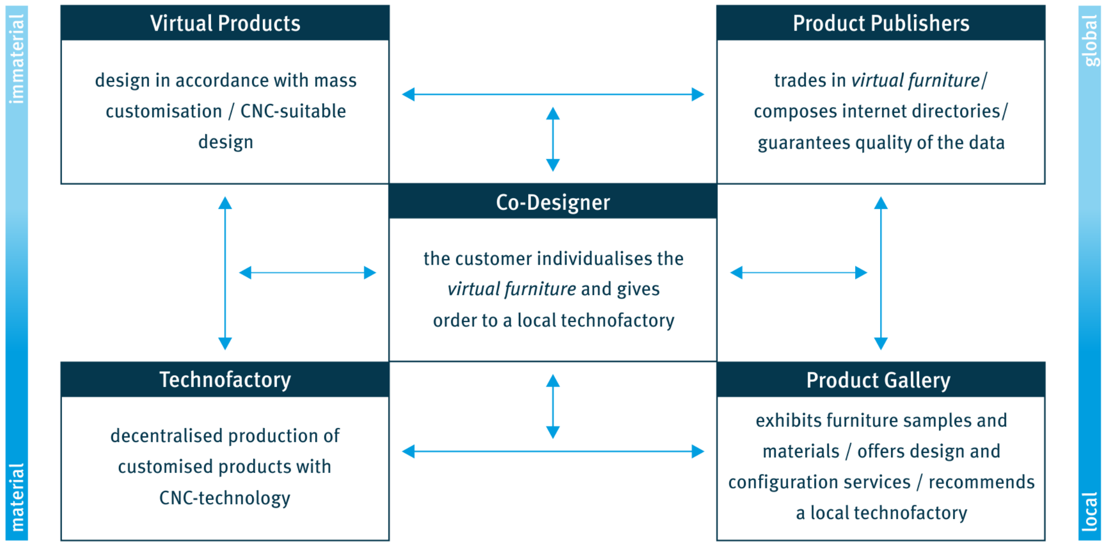

Figure 7. Virtual production scenario (adapted from Steffen, 2006)

According to this model, a 'product publisher' is both a repository and a configuration website that contains virtual products developed by designers to suit company and user needs. A 'technofactory' is a unique CNC production centre or set of centres that collaborate to execute production on demand. A 'product gallery' is the equivalent of a showroom, displaying material samples, products and consultancy services to guide the user during the customisation activities. The 'customer as co-designer' encompasses the customisation activities performed by the user. The goal is to enable users to customise a product using a website configurator or product gallery and send it across the internet to one of the technofactories to be produced.

This long-term research project enabled several variables to be studied in the transition from mass production to mass customisation. The roles of the user, designer and producers, the establishment of collaborative networks, and the translation of files and product semantics were some of the issues that emerged from mass customisation. In presenting the results, Dagmar Steffen (2006) concluded that the pilot project with the technofactories had not succeeded, citing lack of marketing experience as a reason for failing to break into the market. In addition, the product publishers and product galleries had not been implemented.

Gros (2001) discussed the implications of mass customisation for the product design profession. He argued that reduction of typologies and creation of versions were the major tasks to be performed by the designer.

2.1.4. The Consumer

Toffler (1970) claimed that technology and automation would gradually transform manufacturing into a service industry capable of offering lower costs and greater variety. As a consequence, new patterns for consumer relations would be developed. Some of these patterns can already be seen in MC, whilst others are still evolving. They can be summarised on three levels.

The first level relates to MP and early MC, characterised by low costs and availability and catering for basic consumer needs. Availability and affordability of choice changed consumer behaviour, creating a more active demand for customisation.

These features led to the emergence of the second level – mass customisation – in which consumers became co-authors by selecting features of the product before acquisition. Toffler (1970, p. 139) described this level as having the "greatest variety of unstandardized goods and services any society has ever seen."

The third level of evolution is the 'prosumer', a term coined in *The Third Wave* (1989, p. 266). Its definition encompasses the gradual blurring of the roles of producer and consumer. Producers deliberately give consumers some control, by involving the latter in activities the former used to perform. Another shift is created by the do-it-yourself (DIY) setting (1989, p. 271) in which consumers build their own products, turning to producers to provide specific knowledge.

Toffler's concepts summarise MC development. As Piller (2004, p. 329) recalls, the first generation of MC was characterised by production efficiency, particularly with the introduction of FMS and CIM. In the second level, companies developed their strategy to focus on customers and used the internet as a way of enabling technology to interact with consumers. The third level uses MC principles such as customer knowledge and open innovation as a basis for improving MP processes.

This subsection discusses the state of the art of the second level of MC development, focusing on producer and consumer relations, mediated by the use of configurators.

2.1.4.1. Configurators

In MC literature the co-design process refers to the customer's interaction with the company in selecting the final configuration of a product. It is a definition that differs from user-centred design or participatory design concepts in design literature, which refer to collaboration in terms of the requirements and conceptual design phases of the design process.

Co-design refers to the cooperation between customer and company. The consumer, however, modifies a pre-designed solution to suit his/her particular needs, whereas companies define the product family architecture and the range of possible variety autonomously during their product development process (Jiao et al., 2007). During the product family architecture development process, companies employ 'customer sensitivity' (Hart, 1995) as a means of understanding customer needs. Subsequently, as part of their own internal product development process they determine a solution space (von Hippel, 2001; Spahi & Hosni, 2007), which is the degree of change a PFA can accommodate. This definition is optimised according to the production and logistics capabilities of the company (Pine et al., 2000; Piller & Berger, 2003).

Elicitation (Zipkin, 2001) is the mechanism that provides for interaction with the consumer, thus enabling the customisation activities to take place. According to Zipkin, identification, selection of features from a menu, physical measurements, and reaction to prototypes are the four types of information required for consumer interaction. The most common elicitation mechanisms are "(...) known as configurators, choice boards, design systems, toolkits, or co-design-platforms" (Piller, 2004, p. 318).

Configurators are customer relationship management tools that serve two major purposes: they enable design adjustment and provide information for the company. They can be analysed as information systems which mediate between the customer and the company via an interconnected system consisting of a frontend and a backend application (Blecker et al., 2004). The frontend application enables consumers to change the fit, style, and functionality of the product before acquisition (Piller, 2004). This information is transferred in real time via the internet directly into backend manufacturing and logistics specifications, thereby enabling the production on demand.

2.1.4.1.1. Frontend

The frontend application of configurators is the graphic user interface (GUI) that enables product features to be selected. Piller (2004, p. 320–322) proposes three levels for analysing customisation of product attributes: style, fit and comfort, and functionality. According to the author, 'style' relates to the aesthetics features of the product. 'Fit and comfort' relate to the dimensions of the product and is the main reason users want to customise products. However, as Piller affirms, it is the most difficult aspect to develop and to implement, requiring product family architectures with high degree of flexibility, which must be translated into effective configurators encompassing the appropriate level of interaction for customers. 'Functionality' relates to the selection of the technical specification of products. This level can be addressed either before or after the acquisition in the case of technological products with embedded configurators.

Each of Piller's levels relates to a different MC strategy and a particular product design issue. They can be clearly understood by cross-referencing the three levels of product attributes with the degree of customer involvement in the production cycle (Duray et al., 2000). The following summary is therefore proposed:

'Style' relates to the colour, finish and material properties of the product. Modularity enables these features to be combined in the assembly process, resulting in different product versions. Companies therefore employ ATO strategies which push customer involvement to the latter processes of the production cycle;

'Fit and comfort' relate to shape properties, and therefore also the design and fabrication processes. Duray et al. (2000) state that this level of consumer participation allows for a higher degree of customisation, an attribute that means it can be categorised as close to full customisation. Nevertheless, as Zipkin (2001) notes, there are varying degrees of complexity involved in implementing this type of customisation, according to the spatial dimensions of the product;

'Functionality' relates to technical product attributes and depends on the complexity of the product. In low technology products, functionality can be customised on use, by varying the modules to achieve different configurations. In high technology products, functionality can also be built-in (Salvador et al., 2009). The authors exemplify the case of a running shoe with an embedded configurator that automatically adjusts the cushioning of the sole, by measuring the amount of compression submitted to the runner when his/her foot touches the ground.

In terms of the specific area of this thesis, the use of configurators is well established in the furniture industry, particularly in the chair typology. According to the three levels of product attributes defined by Piller, furniture configurators are largely based on style. Selection of colours, materials and finish is a ubiquitous elicitation strategy, since it relies on modular design to provide consumer choice. Fit and comfort is a less common elicitation strategy: in chair design it is used for office chairs, offering a choice from amongst the standard sizes recommended for the range of anthropometric percentiles (e.g. Aeron chairs (Herman Miller, 2014)). Functionality in configurators is usually associated with the selection of armrests and leg height (selecting between table or bar height.)

2.1.4.1.2. Usability

Configurator usability is a subject that depends on product complexity, the number of options given to the customer (Kuester & Buys, 2009) and the consumer's level of experience in customisation (Blecker et al., 2004).

Huffman and Kahn (1998) studied variety in the MC shopping experience and their conclusions may be relevant to the encoding of configurator properties. They suggested cooperation between producers and non-expert customers to help to improve the design of the information presented for selection. Moreover, they concluded that consumers tended to perceive the selection of attributes as less complex than the choice of alternatives. This led to faster learning about product attributes and greater satisfaction within the shopping experience, from selection to acquisition.

The definition of configurators requires an adequate number of parameters that fit the customer's rationale for preferences and a GUI that allows for proper interaction (Heiskala et al., 2007, p. 25).

Blecker et al. (2004) propose that configurators should have the capacity to assist customers throughout the customisation activities, to help them express technical specifications. They conceptualised a configurator containing the product model and an advisory system that guides the customer during the selection activity. The decoupling of the two systems means that the frontend application can present a different logic from the backend application.

"Thus, the method with which the product is modeled is a decision that can be made without considering the customer's perspective. (...) the advisory system is capable of interacting with customers in a nontechnical language and translates their needs into technical product specifications" (Blecker et al., 2004, p. 34).

Moreover, the authors propose that customers should have access to the internal logic of the configurator, according to their needs, knowledge, and level of expertise.

However, the design requirements for configurators extend beyond product attributes and user interface issues. They must respond to user experience issues, since the shopping experience becomes a service. Because the product is configured via a virtual interface, the customer must wait days or weeks to receive the product (Piller, 2004, p. 324). Consequently, since the real experience with the customised physical product is fairly postponed from the act of acquisition, the customer may face issues in claiming to the manufacturer a possible discontentment with the product.

The literature contains empirical studies which compare the advantages and disadvantages of the use of configurators. However, there is a lack of research on the features which define a good configurator for a particular situation (Heiskala et al., 2007, p. 27).

2.1.4.1.3. Backend

Configurators link product family architecture to customers and allow for direct interaction with the company. The backend functionality of configurators is therefore directly related to internal company operations, such as design, manufacturing, marketing and sales.

Salvador et al. (2009) identified that the interaction between consumers and configurators and innovation toolkits provides valuable information for the company. According to this premise, configurators are also marketing tools (Piller, 2004) since they collect consumer data from the orders and selection activity (even if there is no order.) The company's analysis and interpretation of data enable it to initiate new iteration cycles. In particular, it provides reliable information that can be used to refine the product solution space according to consumer preferences, optimise algorithms that control certain configurators' features, or provide better assistance during the configuration experience. Virtual concept testing offers another advantage for companies (Salvador et al., 2009). The use of virtual models reduces stocking costs and allows for production on demand of components.

Furthermore, information exchange "(...) offers possibilities for building up a lasting relationship. Once the customer has successfully purchased an individual item, the knowledge acquired by the manufacturer represents a considerable barrier against switching suppliers" (Piller, 2004, p. 315).

2.1.5. The Prosumer

The gradual blurring of the role of consumer and producer is a consequence of information technology (Toffler, 1989). The central issue concerns the addition of new ideas to the creation of value (Tapscott, 1995, p. 8). As mentioned in the previous subsection, there is a leverage of relations between consumers and companies, since enterprises deliberately empower consumers to participate in the design process. This allows for multiple forms of collaboration between companies and individual consumers, companies and communities of consumers, and within communities of consumers, which has led to a range of terms such as co-creation, co-production, open innovation, open source, crowdsourcing, crowdfunding, prosumption and DIY communities.

This subsection reviews the state of the art of the multiple relations between consumer and producer from a chronological perspective, focusing on product design and the B2C segment. The goal is to present and analyse the evolution of these intersecting roles and the principle arrangements that might occur.

The terms are described in relation three vectors: the different levels of consumer expertise, the type of value created, and their role as promoters of actions. Consumers are categorised as lead users/expert users and non-expert users. Their participation is considered in terms of the creation of use or exchange value, a concept borrowed from Humphreys and Grayson (2008), who employed Marx's distinction in their analysis of intersecting consumer and producer roles. 'Promoter of action' classifies the starting point for action, depending on whether it is a company-based, consumer-based, or mix-model approach.

2.1.5.1. Innovation toolkits

Von Hippel (1977) characterised user ability to innovate (in the B2B market) as a pattern that has played a major role in different industries, such as computer software and food products.

His conceptual model focused on the information being traded between users and manufacturers, and on how information could be transformed into product innovation and business revenue. The importance of the concept relies on the fact that R&D activities can be decoupled, which from the manufacturer's perspective, reduces the investment risk. Decoupling leads to the possibility of outsourcing R&D activities to users or suppliers, then interpreting them to make this information available to the market, according to the company's business model.

The author envisaged user toolkits for innovation (2001) as an interactive tool that allows users to engage in the design specification of a product and be able to innovate.

Von Hippel's theoretical definition of toolkits encompasses important notions for the concept of the prosumer. Firstly, companies can outsource innovation tasks to users through a proprietary interaction system. Secondly, there are different levels of consumers, some of whom, namely the lead users, express an interest in spending more time engaging in trial-and-error activities during product configuration. Thirdly, toolkits must be developed in several iterations, fostering collaboration between the producer, expert users and communities of expert users.

The author envisaged that the development of this type of application by one company would encourage consumers to use it and competitors to follow this approach. One potential disadvantage would involve customers developing their own tools and becoming direct competitors.

Von Hippel's concept is different from configurators. Configurators are company-based interaction systems suitable for both non-expert and expert users which create use value through the selection of pre-determined choices. User toolkits for innovation are company-based interaction systems suitable for expert users which create use value but also exchange value through the user's active participation. Between these two approaches, several others can be identified which vary in terms of the level of relationship between users and companies.

One example is the Fiat 500 redesign (Salvador et al., 2009). To support the planning and task clarification and conceptual phases of the design process, the brand created the Concept Lab, which was an innovation toolkit not suitable for configuring an order, but for outsourcing interior design layouts. The innovation toolkit received more than 160 000 designs from the online community, along with ratings and comments. This tool allowed the company to collect data on consumer preferences.

Another approach which combines use value with exchange value can be exemplified by two Lego platforms: 'Mindstorms', launched in 1998 and 'Lego Factory', launched in 2009.

In Mindstorms, Lego allowed expert users to construct their own toolkits in ways that extended beyond the company's initial planning and required a reconfiguration of the initial strategy to cope with user development (Tapscott & Williams, 2006, p. 130–131). Furthermore, Lego involved the first generation of expert users in the development of the redesign of the product (Tidd & Bessant, 2009b, p. 322).

The Lego Factory approach was defined as an open innovation strategy from the outset. Implemented as an online community where users submitted their designs using proprietary Lego software, it allowed them to share designs and earn royalties from sales (Tidd & Bessant, 2009a).

User toolkits for innovation can be seen as the 'configurators' for open innovation, since they are the connecting interface between companies and users.

2.1.5.2. Open innovation

Chesbrough (2003) characterised how R&D knowledge was managed in high technology institutions and, in particular, how scientific and technological breakthroughs were transformed into products and services to generate value. The author described open innovation as an opposite model to closed innovation, a paradigm of R&D management characterised by the generation, development, and commercialisation of ideas generated uniquely from internal resources. In open innovation there is greater interaction between the company and its stakeholders in order to create exchange value. Companies generate, co-develop or acquire ideas both from in-house departments and/or outside companies and/or individuals. They then integrate them into their business models to generate value.

The model comprises two major approaches: the outside-in approach, in which companies commercialise ideas and technologies developed outside the company, and the inside-out approach, in which companies make innovations available on the market if they do not suit their business models. The former approach had been the prevalent one, allowing companies to develop new products more quickly, whilst also reducing costs (Chesbrough & Crowther, 2006). The authors observed that most of the companies had been using open innovation as a tool to achieve growth and defend their businesses rather than to leverage market competition.

Successful cases of open innovation reveal organisations sharing some intellectual property to allow for collaboration with individuals and online communities (Tapscott & Williams, 2006, p. 9). The authors describe, amongst others, an example from Goldcorp which illustrates this description (2006, p. 7–10). Goldcorp is a Canadian gold-mining company that created an online challenge in 2000 to find new sites. They opened up their proprietary geological data and asked participants to prospect in exchange for a prize. They estimated that the open innovation process cut traditional R&D time by three years. They also observed that, in addition to geologists, people from different disciplines had participated and contributed to knowledge that was not applicable in the industry.

Open innovation allows individuals, amateurs and smaller companies to be R&D suppliers (Tapscott & Williams, 2006, p. 105). Moreover, it provides the ability to transform underused technologies into new applications. Open innovation can be interpreted as virtual enterprise and the embodiment of the twelve themes of the new economy conceptualised by Tapscott (1995, p. 44).

2.1.5.3. Open source

Open source is a term coined in 1998 by founders of the Open Source Initiative (OSI) (Internet Archive, 2014; Open Source Initiative, 1998) to describe the philosophy underlying the development and distribution of free software. The definition of open source states that original software and its source code can be redistributed freely and modified by any individual, according to the integrity of the author's source code. Moreover, the license allows for the development of related work under the same terms as the original source. The goal is to develop better software, improved by the community of users, which primarily promotes use value.

The open source definition was adapted to hardware as follows (OSHWA, 2014):

“Open source hardware is hardware whose design is made publicly available so that anyone can study, modify, distribute, make, and sell the design or hardware based on that design. The hardware’s source, the design from which it is made, is available in the preferred format for making modifications to it. Ideally, open source hardware uses readily-available components and materials, standard processes, open infrastructure, unrestricted content, and open-source design tools to maximize the ability of individuals to make and use hardware. Open source hardware gives people the freedom to control their technology while sharing knowledge and encouraging commerce through the open exchange of designs.”

The open source concept evolved into a generic definition that ranges from software to hardware and from services to goods, which can be summarised as a production philosophy that encompasses open access to design and development knowledge that can be continually improved and remixed by peer production.

Open source covers a range of licenses (Open Source Initiative, 2014; Creative Commons, 2014a) which allow for the commercial application of software or products developed in collaborative fashion by the user community. The difference between this and proprietary knowledge is that the author cannot place restrictions on users who modify the original product and develop commercial applications from it.

Examples of open source hardware projects (Wikipedia, 2014) cover a range of artefacts and scales, including furniture (Open Desk, 2014), houses (Parvin et al., 2014), machines (RepRap, 2014), and vehicles (OSVehicle, 2014), amongst others.

Ronen Kadushin’s 2005 open design approach for product design (Kadushin, 2014) has been followed in different ways, one example of which is the Diatom studio (2011a) SketchChair project. The studio used a construction system codified into software capable of designing customised versions, analysing structural stability and generating digital fabrication files for CNC routing. The free open-source software is based on a GUI enabling two-dimensional representation that enables the user to design his/her own chair and share or download designs from others. The final design system was developed through a crowdfunding campaign that gathered the support of 584 individuals (Diatom, 2011b).

The development of one design system determines the evolution or availability of other systems. Mattermachine (2014) builds upon the SketchChair customisation premises but provides direct access to the user interface via the internet. The GUI is based on three-dimensional visualisation and allows for customisation of parametric designs and real-time information on the price of the design. The design system enables the source code to be edited by expert users.

Both approaches require a different type of user from the one that interacts with configurators. These design systems require a user versed in CAD techniques to customise the shape of the final object, together with the ability to abstract between two-dimensional and three-dimensional representations, and a knowledge of digital manufacturing.

Chesbrough (2003) classifies open source as a movement of innovation missionaries, characterised by groups of people and organisations that do not have financial gain as their goal. Although use value is the principal motivation, the definition also includes exchange value. Peer production and open source generate commercial applications (e.g. Anderson, 2012, p. 102), representing a bottom-up approach to the market and allowing for multiple forms of relations between users and companies. Tapscott and Williams (2006, p. 16) cite Bill Gates to describe how open collaboration may represent a potential threat to established business models.

2.1.5.4. Crowdsourcing

Open innovation can be considered a predominately top-down approach developed by established companies which open up their product development processes, both internally and externally, to participation by individuals and other stakeholders. Open source can be interpreted mainly as a bottom-up approach in which groups of users create their applications, which can evolve into the creation of companies. Both open source and open innovation disrupt the traditional company system and offer multiple modes of collaboration between producers and consumers.

Crowdsourcing, a term coined by Jeff Howe (2006) combining 'crowd' and 'outsourcing', was used to describe the phenomenon of 'open call' on the internet, which relies on the networking skills of engaged individuals willing to contribute to activities traditionally carried out by company employees.

Certain interpretations consider crowdsourcing equivalent to open innovation. In the interpretation used here, there are differences between these two concepts. Open innovation encompasses different approaches that may or may not involve a crowd, whereas in crowdsourcing this principle relies on Howe's original definition. According to Bartling and Friesike (2014) the use of crowdsourcing excels the exclusive top-down or bottom-up approaches.

Paulini et al. (2013) distinguish two end points in a continuum of crowdsourcing approaches in design: collective design and collected design. Collective design comprises high levels of collaboration between individuals in the search for a solution, whereas collected design is characterised by individual solutions submitted in response to an open call.

2.1.5.4.1. Collective design

Paulini (2012, p. 20–21) observed different patterns while comparing the collective design activity in online communities with the design activity performed by teams in participatory design. The author analysed the participants' professional backgrounds, their motivation, task assignment, period of time engaging in design tasks, and medium of interaction with other team members.

In collective design, the participants come from different professional backgrounds. Their participation in the design process is voluntary and decided according to their own motivations and skills. They select the task or set of tasks they want to perform and they manage their own time. The interaction with other participants is mediated by the internet, often not occurring in real-time.

In participatory design, each participant's professional background or experience is taken into account in the constitution of the design teams. The participation is maintained during the design process, according to a specific time schedule defined from the outset. The tasks are assigned according to the expertise of each member. The interaction between participants may whether occur in real-time in a physical space or be computer-mediated.

According to the author, online collective design platforms act as social networks designed to promote different degrees of interaction, offering each member the opportunity to contribute according to his/her own time and interest.

Paulini et al. (2013) analysed platforms in which the 'open call' was presented according to a structured model of the design process. The division into equivalent phases of generation, development, and evaluation with a precise time schedule led to adequate participation by users with different levels of expertise and interest. Diverse information input and different channels of communication supported the collaborative development of ideas. The authors compared communication levels in collective design platforms with computer-mediated collaborative design and face-to-face design, and concluded that communication was higher in collective design environments (29% as opposed to 7%-8%, and 5%, respectively.)

Two platforms were selected from the authors' study to illustrate the premise that crowdsourcing permits different types of approaches. Although the platforms share similarities in terms of the design process and types of user interaction, they also present different business models.

Quirky (2014) is a hybrid business model. The design process accommodates the input of ideas from users and their participation in the selection of the concepts that are created in the generation phase. During the development and evaluation phases, concepts are refined according to feedback from users. Branding material, such as naming and logos, are also discussed collectively. When the crowdsourced ideation process is completed, the Quirky team continues to the next phases. The product development process is handled internally: the product design team develops the product, whereas engineering and logistics prepare the manufacturing and distribution processes (Anderson, 2012, p. 179). At the end of the product development process, Quirky pre-sells designs (before production) in a similar way to the crowdfunding platforms (Agrawal et al., 2010). User influence on the final design is measured and Quirky calculates the percentage of each user's influence and pays a royalty on product sales.

OpenIdeo (2014a) is an open innovation platform where ideas are decided on by both the company and partners and then presented to the crowd. User participation is “entirely voluntary, non-confidential and gratuitous” (OpenIDEO, 2014b).

2.1.5.4.2. Collected designs

In collected design, there is no collaboration during the design process and content is produced from final designs submitted by users. Two types of enabling platforms – service providers and capital providers – are classified here.

Service providers (e.g. Shapeways, Ponoko, Zazzle, Thingiverse) are business models that allow users to submit digital models for production. The uploaded design can be ordered for self-production and it is also possible to license the digital model in a variety of ways (Creative Commons, 2014b), thus enabling the user to share or sell the design. Service providers employ production processes such as printing, laser cutting and 3D printing. CNC milling is not common in these types of crowdsourcing platforms (Ponoko, 2013).

The crowdfunding platforms are the capital providers. They are the equivalent of venture capital decoupling and enable users to fund their projects.

“Over the past few years, a new phenomenon of “crowdfunding” has taken off, by which supporters and potential customers collectively contribute the money necessary to get the product made. (...) Rather than just making a donation, most contributors essentially preorder the product by making a contribution above a certain level” (Anderson, 2012, p. 166).

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2.2. Digital Design

CAD systems have long evolved from the accurate representation of basic shapes in a computer system (Sutherland, 1963) to assisting product development processes from concept to manufacturing through the integration of CAE and CAM (Bézier, 1998; Myers, 1998).

This section presents the state of the art in digital design. It builds on the established principle that digital design tools are commonly used in product design methodology to assist the conceptual design, embodiment design, detail design and production phases of the design process, and the manufacturing processes. Rather than reviewing the adoption of these tools, it therefore discusses their instrumental capacity within a changing model of thought, practice, and output.

A plethora of perspectives and classifications can be used to describe the integration and application of digital design tools as a standard practice in the processes of designing and producing three-dimensional artefacts. The difficulty of a unique comprehensive model derives from the fact that the concepts relate to product design, engineering, and architecture. Each discipline has multiple applications, different rates for adopting new technologies and prior traditional practices, in addition to interdisciplinary territories. Moreover, the characteristics of the product development process (e.g. the number of team members, degree of automation in other steps of the design process, and the manufacturing process) and the product features (e.g. complexity, scale, number of components) must be added to the variables that characterise this domain.

Rivka Oxman (2006) defined four[2] models that accommodate specific sets of interactions between designer and digital media to characterise professional practice supported by these tools. Oxman developed the models by considering their application in architectural design practice, stating that similar principles were observed in product design. Oxman's models are used here exclusively to characterise product design practice, therefore including minor changes to the original conceptualisation.

The aim of this section is to examine specific techniques and methods that support the establishment of a digital design methodology. The section begins by presenting digital design methods and practices according to Oxman's models. The second subsection characterises shape grammar as a generative design mechanism. Its concepts, applications and techniques are reviewed in order to discuss the aspects of design thinking that are amenable to digital implementation. The third subsection focuses on the challenges of classifying parametric models and parametric design, supporting the examination of design thinking and design practice issues associated with the use of parametric software. The fourth subsection discusses the link between parametric models and optimisation tools.

[2] The paper comprises a fifth, the compound model, which is an envisaged theoretical proposition.

2.2.1. Digital Design Models

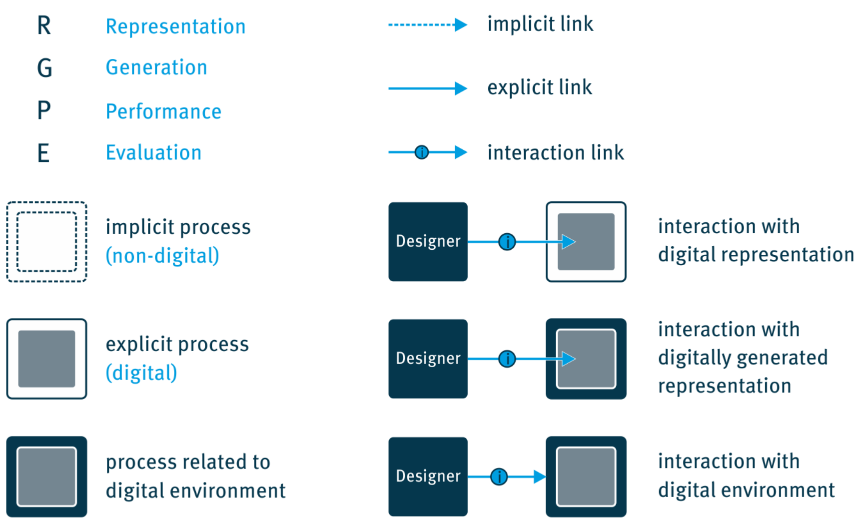


Figure 8. Symbols, boundaries and links (adapted from Oxman, 2006, p.242)

Oxman established the four models of digital design practice by analysing the interaction between the designer and the computer-aided design tools, in performing four design activities: representation, generation, performance, and evaluation. Representation and generation have a stronger basis in design practice, whereas evaluation and performance are derived from engineering practice.

The four models are CAD models, digital formation models, performance based-models and generative models. Figure 8 shows the symbols, boundaries and links used to describe the models.

2.2.1.1. CAD Models

"The industrial designer manipulates virtual 3D forms, via the computer screen and input devices such as keyboard and mouse, to create the final desired form. Rendering applications can then be used to visualise these models as realistic 2D images which can be used for communication and evaluation in the same way that conventional physical 2D rendering is used" (Evans & Wormald, 1993, p. 98).

Figure 9a illustrates the interaction between the designer and traditional CAD. Evans and Wormald considered this subtype of CAD model to comprise low-level virtual models which served the purpose of visualisation and animation. The output takes the form of technical drawings or renderings. With the incorporation of ray tracing algorithms in the CAD software (first used in animation software), the rendering setup introduces physical constraints into the digital construction of the models, particularly in the definition of light and shadow parameters.

In Figure 9b there is a connection between the CAD software and the CAE software. CAE supplement geometrical data with analytical data. The goal is to predict the behaviour of the object under real world conditions by running simulations. The results lead to the manual refinement of the CAD representation and a new iteration of the loop. The inclusion of evaluation in the product design methodology enhances design quality by addressing the predictive behaviour of a design in the early phases of the design process (Adams & Askenazi, 1999, p. 18).

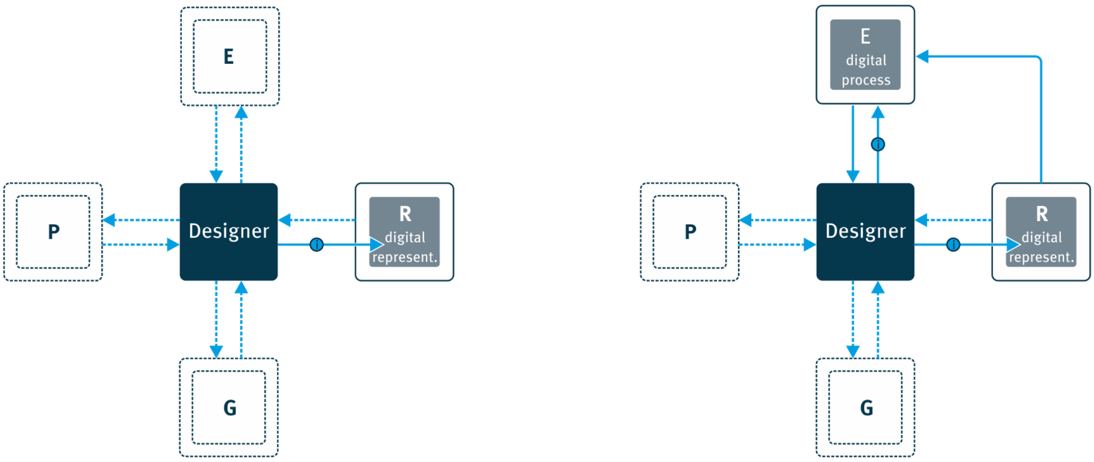


Figure 9. CAD models: a) Traditional CAD model; b) CAD-CAE model (adapted from Oxman, 2006, pp.247-248).

CAE includes different techniques, according to the subject of the analysis. FEA enables the analysis of the effect of real-world conditions submitted to an object, such as stress, deformation, temperature or vibration (Adams & Askenazi, 1999, p. 11). In the field of structural mechanics, FEM is the main analytical method (Macneal, 1994, p. 1). The CAD geometrical model is transformed into a discrete digital model, composed of a finite number of elements. This mathematical formulation calculates the whole structure comprising sub-calculations of the force-displacement relationship for each element (Zienkiewicz & Taylor, 2000 [1967], p. 2).

CAD and CAE integration requires different models to the ones generated for visualisation purposes. Evans and Wormald refer to the production of high-level CAD models. These are robust models produced in the early steps of the design process that are suitable for the latter steps of the design process and for the production process. According to the authors, the possibility of using such type of models would improve the design process, by reducing the time from conceptual design phase to production phase. In practice, the sequence of tasks would be improved due to the ability of designers and engineers for working concurrently on the same high-level CAD model (Evans & Wormald, 1993, p. 99).

Although the integration of CAD and CAE favours interdisciplinary practices, there are potential issues, as summarised by Gujarati and Ma (2011, p. 118):

"(1) information losses; (2) compatibility issues between data structures; (3) breakdown of associations; (4) lack of reusability of knowledge; (5) the conflict of complex geometry and its analysis simplification requirement; (6) loss of design expertise; (7) difficulties in automation of the design process; (8) unacceptable time associated with the total design cycles; (9) geometry simplification of CAD model and the conversion to FEA model for mesh generation and analysis."

2.2.1.2. Digital Formation Models

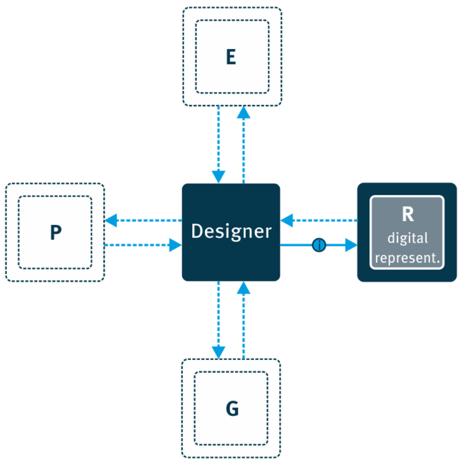


Figure 10. Digital formation model (adapted from Oxman, 2006, p.250)

Oxman (2006, p. 249) characterises digital formation models as "dynamic concepts that are creating a new definition of the role of representation itself."

The term 'formation' is the dynamic counterpart of 'form', as it encompasses the experimentation with shapes within CAD software. Whereas in the CAD model the designer uses digital tools to represent a previously defined concept, in digital formation CAD software is employed as an auxiliary tool for concept generation and exploration. The designer interacts and directly controls a digitally generated representation (Figure 10).

This model offers new types of relations between designer, design, and representation. The design intention is represented in an earlier step of the design process, during the conceptual design phase. The goal is to expand the conceptual possibilities and represent additional instances of the design intention. Software capabilities to compute geometry, combined with additional algorithms to reconfigure shape, represent a different approach to the way CAD software is used. Digital tools therefore become 'enabling environments' that increase the capacity to represent multiple instances of the same concept. Oxman specifies three sub-categories of digital formation models: topological, associative and motion-based models.

In topological models, designers maintain the object topology and shape exploration is undertaken by exploring transformations of the geometrical elements of construction rather than geometry as a whole. The digital reconfiguration is assisted by digital modifiers.

Associative models are based on the parametric exploration of associative geometry. The designer establishes constrained relationships between parts of the geometrical model that are capable of providing variations when different values are assigned to dimensional parameters (Monedero, 1997). This type of interaction with the internal logic of design formation determines a shift in the design approach, which then focuses on defining the transformational reconfiguration schema.

Motion-based models borrow computer animation techniques to explore a dynamic formation process. Techniques such as morphing, inverse kinematics and keyframe animation support the shape exploration processes.

This type of approach, enabled by CAD software, had a major influence on shape configuration in the 1990s and early 2000s. The resurgence of the organic form, termed ‘blobject’ in 1993 (Holt & Skov, 2005, p. 8), was widely adopted as a design style, due to the possibilities afforded by digital design (Figure 11).

Name	Rock (doorstop)
Designer	Marc Newson (1963-)
Manufacturer	Magis, Italy (1998)
Materials	Blow-moulded polyethylene.
Size (mm)	Lenght 230, width 150, height 120

Name	S2 Sports CD/ radio tuner
Designer	Sony Design Center
Manufacturer	Sony, Japan (2001)
Materials	Injected ABS
Size (mm)	Lenght 431, width 279, height 165

Name	Rio Sport S35S digital audio player
Designer	NewDealDesign
Manufacturer	Digital Networks, USA (2003)
Materials	Injected ABS
Size (mm)	Height 74, width 66, depth 25

Name	A.U. chairs
Designer	Studio I.T.O
Manufacturer	Edra, Italy (2003)
Materials	Moulded polyurethane foam, stretch fabric, leather, plastic base
Size (mm)	Small sofa: H 760, W1460, D 1300. Chair: H 700, W1160, D 920

Figure 11. Blobjects

(Source: a) Magis, 2012; b) Holt & Skov, 2005, p. 63; Amazon, 2003; c) Holt & Skov, 2005, p. 135; PC World, 2003; d) Edra, 2014)

2.2.1.3. The Generative Model

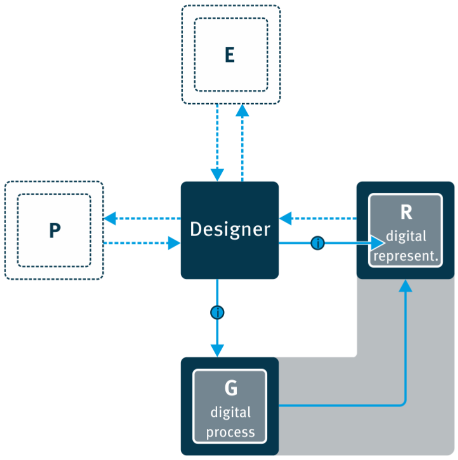


Figure 12. Generative model (adapted from Oxman, 2006, p.255)

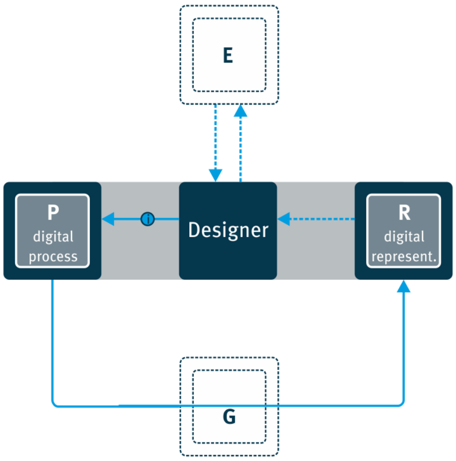
In CAD models the designer represents the geometrical aspects of the designed object, while in digital formation models there is the interaction with both the geometrical and topological aspects. In generative models the designer interacts with the underlying mechanism that explains the generative features of digital representations (Figure 12). Oxman distinguished between two main formalisms: shape grammars and evolutionary models.

"Shape grammar as a generative mechanism based upon formal compositional rules is perhaps the most interesting case to examine the problematic of a priori formal content in digital design" (Oxman, 2006, p. 255).

In shape grammars, design results from the application of step-by-step rules. These can explain spatial relations, material, and semantic properties (Stiny and Gips, 1972). In evolutionary models, design results from scripted algorithms that simulate biological evolutionary processes. Genetic algorithms (GA), developed by Holland in 1960s (Holland, 1992), mimic evolutionary mechanisms such as the genetic code and selective breeding to achieve the best solution for a particular set of conditions. Bentley and Wakefield pioneered the use of GA to deal with concept generation issues in product design applications. Their experimentation with tables (1995) and optical prisms (1996) provided the opportunity to test the suitability of GA for early steps of the conceptual design phase.

GA has been most commonly applied as a stochastic method of optimisation. Hsiao et al. (2010) used GA to optimise the shape of coffeemakers by developing an algorithm that deals with semantic properties to guide the selection process. Consumers evaluated seven linguistic variables defined by designers and the results were then encoded into the GA.

2.2.1.4. Performance-Based Models



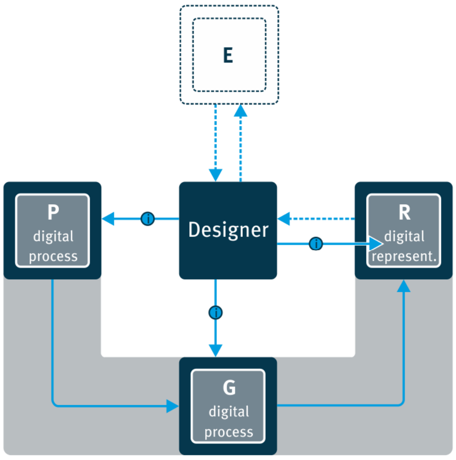


Figure 13. Performance-based models: a) Formation model; b) Generation CAD-CAE model (adapted from Oxman, 2006, p.255).

Performance-based models are interactive evaluation models which allow for automated shape refinement as a result of simulating real-world conditions (Oxman, 2006, p. 257). Oxman distinguished two sub-classes: formation and generative.

Figure 13a shows direct designer interaction with analytical tools in performance-based formation models. The results of the simulation determine the conditions for generating optimised shapes. In this case there is no formal generative model.

Figure 13b illustrates generation models. This sub-class provides additional negotiation between modules and the result is a trade-off between the performance criteria, simulation results and generation principles.

Achim Menges and his research group have been applying computational morphogenesis in an integrative way, leveraging material properties with shape goals. The definition of the integrated generative design system requires an analysis and encoding of the material properties, geometric possibilities and manufacturing constraints (Menges, 2007, p. 725–726).

In the generative sub-class, material and manufacturing conditions are not post-rationalisation processes but integral drivers that influence system behaviour. Performance-based tools negotiate with the generative system through iterative cycles to influence the generative mechanism; in Menge's case, the evolutionary process is driven by GA.

2.2.1.5. Discussion

Design activity with the use of digital tools commonly raises questions about the role of the designer and the extent to which digital tools become an end, rather than a means. Data generation, handling, editing, specification and translation (Burry & Burry, 2012, p. 210) become the central issues of designing with digital tools. The designer is able to encode additional variables into the design process, which becomes a system of allocated relations. A computer is given instructions to perform, which means that the design activity is not substituted: the designer defines the system and moderates its behaviour (Menges, 2007, p. 732).

Achten and Joosen (2003), for instance, reviewed an architectural project developed exclusively with digital design tools. Their conclusions highlighted the need to develop mixed methodologies and employ different media during the design process, since certain aspects of the design are better translated using specific methods and techniques, such as sketches or physical models. The authors concluded (2003, p. 272) that the use of digital media alone was impracticable for several reasons. The proficient use of a software requires significant time investment; the exchange of data between software leads to information loss and the inability to reuse design knowledge; the customisation of software to include specific features is difficult and may include an additional set of skills; and the straightforward representation of free-form shapes may lead to a detachment between the digital representation and the physical construction.

The ability to encompass several approaches based on the instrumental level afforded by digital tools challenges established notions of professions, promotes cross-disciplinary collaboration and addresses the problem of how to understand and manage complexity with regard to the goal of defining a design solution. These changes may ultimately lead to an extension of the traditional role of the designer, from a user of digital tools, to a 'tool builder'. According to Robert Aish (cited in Oxman, 2006, p. 253), a "tool builder can define his own generative components and define their transformational behavior."

2.2.2. Shape Grammars

Shape grammar is a formalism defined by Stiny and Gips (1972) having as a reference Chomsky's generative grammar (Stiny, 2006, p. 18). It permits the creation and description of design languages through four key concepts: a set of geometrical shapes; a set of spatial relations between them; a set of composition rules that recreates such spatial relations; and an initial shape to which these rules can be applied recursively to generate different designs (Stiny, 1980a). Shape grammars operate as spatial algorithms (Knight, 2000) that explain the generative properties of shapes, their decomposition into sub-shape, and Boolean operations on them (Stiny, 1991).

2.2.2.1. Properties

Shapes are described in algebra U_{nm}, in which *n* is the dimension of objects and *m* the dimension of the space in which objects are combined (Stiny, 1990). Points have zero dimensions, whereas lines have one dimension, planes two dimensions, and solids three dimensions. The algebra U_{01}, for instance, consists of a set of points arranged along a line and algebra U_{12} consists of lines arranged on a plane.

Since the act of designing includes additional considerations besides the ones related with shape representation, any algebra of shapes (U) can be augmented by algebras of labels (V) and weights (W) (Stiny, 1990; 1992). These algebras maintain the original properties of U and extend the control of shape properties by introducing new layers of information. Labels provide additional control to specify the geometric properties of a shape. Weights enable functional requirements, construction principles, material properties or graphic expression of designs to be represented. These principles enable a shape grammar to be defined as a Cartesian product of different algebras, each containing specific classes of elements.

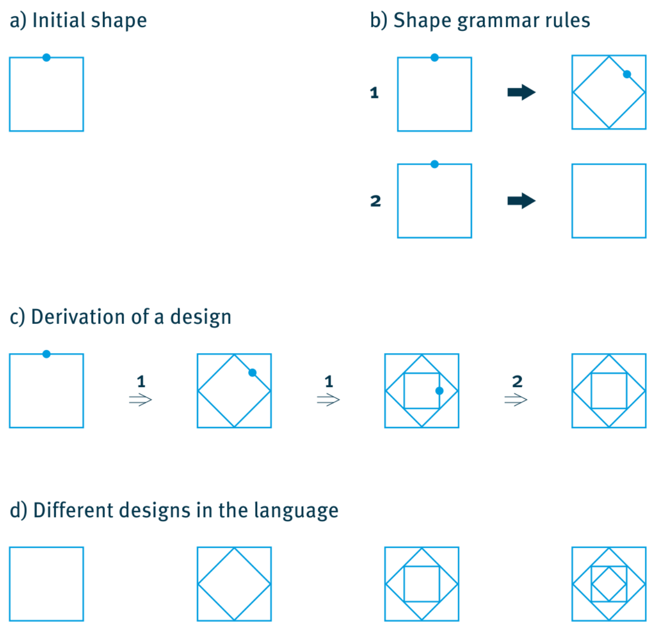


Figure 14. Example of a shape grammar defined by Stiny (adapted from Stiny, 1980a,p. 348)

Shape grammar rules are step-by-step procedures that enable shape computation. They provide for both shape descriptions and the generative explanation of designs. A rule is a visual counterpart of the 'if-then' algorithmic preposition. The left side of the rule is the initial shape condition and the right side the transformation applied by the rule. Rules are applicable when the conditions in the left side are observable in a given design.

Figure 14 illustrates a practical application of shape grammars. An initial shape and two rules define the generative procedures. They define a design language, i.e. a set of individual designs that share a formal resemblance and the principles defined in shape grammar properties.

2.2.2.2. Extensions

In addition to algebras V and W, shape grammars can have other extensions. These extensions can be used to create multiple outputs from the same rule, describe additional properties, increase control of rule application, and create multiple views to assist rule application.

Parametric shape grammars (Stiny, 1980a) are shape grammars in which the rules contain a description of the variation space for the elements. Rule application does not therefore determine a fixed shape; instead the application of the same rule can designate different designs that share the same topological structure but have a different final configuration, achieved by varying the dimensional parameters.

A description grammar is a complementary set of rules that express conditions for applying the spatial rules of a shape grammar (Stiny, 1981). This method enables criteria to be included to guide the generation process. Computation becomes a parallel process of meeting both the requirements of the description grammar and the spatial operations defined in the shape grammar.

2.2.2.3. Types

The application of shape grammars comprises two major types: 1) creation of new design languages and 2) analysis of existing design styles to encode them as design languages (Knight, 1999, 2000). Transformation of shape grammars is a theoretical premise suitable to both types. It permits the iteration of the process of encoding a shape grammar to define new languages based on the previous encoded ones. Knight (1981, 1983b, 1983c) formalised the methods for using an existing shape grammar as the basis for evolving new languages.

The first type, namely the design of original shape grammars (e.g. Stiny, 1976, Stiny, 1980b, Knight, 1989), is an approach similar to that of traditional design processes, in which an ill-defined situation (Cross, 2000, p. 14) is iteratively developed into a structured solution. Nevertheless, the program and outputs are different. The program comprises the definition of vocabulary, spatial relations, shape rules, initial shapes, shape grammars and design languages (Stiny, 1980b). The design intentions are specified in a constructivist fashion by specifying rules to generate designs and refine them according to the trial results. The process has a twofold output: a set of rules that determine the explicit representation of design knowledge, and the generation of multiple versions rather than a unique solution.

The second type comprises shape grammars defined after the analysis of existing design styles. Furthermore, analytical grammars include a hybrid approach that departs from an analytical perspective but whose goal is not analysis *per se*.

The Palladian Villa grammar developed by Stiny and Mitchell in 1978 is the first analytical architectural study. Its procedures established the generic methodology for this type of shape grammar. It comprises a selection of representative existing designs by the author. This set of designs or corpus represents the tacit knowledge of the design style, in the way that it is not explicit for enabling the generation of other instances within the style. Analysis of the corpus guides the iterative process of creating and refining the shape grammar properties. The characterisation of a design language is complete when the shape grammar is set according to the following criteria (Stiny & Mitchell, 1978, p. 17):

"(1) it should clarify the underlying commonality of structure and appearance manifest for the buildings in the corpus; (2) it should supply the conventions and criteria necessary to determine whether any other building not in the original corpus is an instance of the style; and (3) it should provide the compositional machinery needed to design new buildings that are instances of the style."

In architectural design, the analytical approach following this methodology is exemplified by the applications for Frank Lloyd Wright's prairie houses (Koning & Eizenberg, 1981), Queen Anne houses (Flemming, 1987), and Taiwanese traditional housing (Chiou & Krishnamurti, 1995).

There are more applications of analytical grammars than original ones. This is because they can be verified on the basis of empirical knowledge, thus assessing the degree of robustness achieved by the rules that have been developed. This premise determined the possibility of studying the potential of shape grammars as a valid application in the design process.

Hybrid approaches are based on analytical studies but have a wider purpose, namely the application of shape grammars to design practice (Knight, 1999). The shape grammar formalism becomes the central computational device that coordinates the generation process, integrating additional variables into the design process. This type of grammar therefore employs extensions, such as the ones described previously, and often combines them with other computational techniques to increase the instrumental potential of the formalism. The goal is the construction of computational generative mechanisms that can be adapted to model design problems that share similar features.

In combination with other computational techniques, this expanded the application of shape grammars to different fields. In architecture, the discursive Siza Malagueira grammar (Duarte, 2001, p. 341) combined shape grammars and description grammars with optimisation techniques. User requirements establish both the conditions for rule application and the evaluation procedure and a set of heuristics guide rule application by comparing the generated design with the previously stated goal description.

In engineering, the most important applications are based on the evolution of the shape annealing algorithm that combines shape grammars with stochastic optimisation (Cagan &

Mitchell, 1993). This approach was further developed by Shea and applied in the design of optimal truss structures (e.g. Shea & Cagan, 1999; Shea et al., 2005).

2.2.2.4. Strategies

No.	NAME	DOMAIN	STRATEGY	AUTHOR / YEAR
1	Hepplewhite-style	Furniture	Subdivision	(Knight, 1980)
2	Office chairs	Furniture	Additive	(Hsiao & Chen, 1997)
3	Coffeemakers	Domestic ware	Additive	(Agarwal & Cagan, 1998)
4	Motorcycles	Transportation	Additive	(Pugliese & Cagan, 2002)
5	Front view of Buick vehicles	Transportation	Additive	(McCormack et al., 2004)
6	Digital cameras	Consumer electronics	Additive	(Lee & Tang, 2004)
7	Coca-Cola bottles	Packaging	Additive	(Chau et al., 2004)
8	Shampoo bottles	Packaging	Additive	(Chau et al., 2004)
9	Kettles	Domestic ware	Additive	(Prats et al., 2006)
10	Cross-over vehicles	Transportation	Additive	(Orsborn et al., 2006)
11	Ultrasound transducer	Healthcare	Additive	(Culbertson, 2012)
12	Tableware	Domestic ware	Additive	(Castro e Costa & Duarte, 2013)

Table 1. Examples of product design shape grammar applications

Knight (1999, p. 4) categorised the design strategies employed to develop the vocabulary of shapes and shape rules as abstract grid, subdivision, and additive. In the abstract grid strategy (e.g. the Palladian Villa grammar), the grammar first generates a grid that structures the space of the design, and then adds details by further rule application. The subdivision strategy is employed when the language of the designs shares the same boundary. Rule application determines solutions by subdividing an initial shape into sub-shapes. The additive strategy is the one selected when the language of designs has irregular or different boundaries. The initial shape is the core of the structure and other components or elements are then added. These strategies are often combined with the types of grammars described in Section 2.2.2.3.

In Table 1, it can be seen that the additive strategy is the one most commonly used in product design. This type of strategy is used to generate the entire design, whereas the subdivision strategy is applied to generate particular areas. In terms of representation, the subdivision strategy can operate on a higher level of abstraction than the additive strategy. As the boundaries are fixed and the resemblance between the elements represented is stronger, shapes can be simplified. This condition provides the theoretical capacity to create a shape grammar with fewer rules than the additive strategy.

The strategies share similar inference processes. Designs are analysed and decomposed to support rule definition. Decomposition serves the purpose of composition and may not reflect the original intention of the designer, as Knight observes (1999, p.4). The rules express a spatial relationship between components. Prats (2007, p. 81) indicates that the design space is a controlled trade-off between the application of labels to control the functional properties of the shape (limit the space) and parametric properties to expand the space.

2.2.2.5. The Hepplewhite-Style Shape Grammar

The shape grammar defined in this research shares similarities with the Hepplewhite-style shape grammar. A review of this work therefore establishes some of the premises observed in the case study.

The Hepplewhite-style chair-back shape grammar developed by Terry Knight (1980) is the first example of the application of shape grammars to a chair design problem. It addresses a common issue in classic chair design[3], that is the detailing of the shape of the backrest and its elements as the main constituents of the design language.

The shape grammar is parametric and is defined by the subdivision strategy. The methodology encompasses the following steps: selection of a corpus, observational description, analysis, simplification of the representation, definition of the parametric shape grammar properties, and translation from rectilinear to curvilinear shapes.

The corpus consists of a selection of three chairs with different features and represents the tacit design knowledge defined in the Hepplewhite-style[4]. Observational description of the chairs identified the chair back as the distinctive element of the style, whilst the other elements remain similar. Therefore, the shape grammar only describes this specific area. The representation of the chair back was simplified, first by removing decorative motifs and then by representing it as a basic curvilinear shape. After this depiction, the curvilinear representation was simplified into an equivalent rectilinear representation and only half the structure was represented due to symmetry properties. Therefore, the shape grammar is devised based on a higher abstraction model. The complete description comprises the algebras U_{02}, U_{12}, V_{01}, and a set of additional representations specifying the parametric variation spaces to position points.

The generation process concludes with a procedure for the translation from rectilinear into curvilinear representation. A seven-rule shape grammar enables multiple designs to be

[3] Sheraton, Adam, Hepplewhite, Chippendale and Thonet employed this design strategy to create different versions of chairs, as indicated in Oates (1981).

[4] According to Knight (1980, p. 228) the chairs are attributed to the American furniture designer Samuel McIntyre, who designed furniture following the Hepplewhite-style books.

generated, each characterised by a specific topological relationship between the elements (Figure 15). Parametric variation allows for additional exploration of a design.

The Hepplewhite shape grammar encompassed principles that provided a straightforward way of learning and applying the rules to design new solutions. The operational stage of rule application was enhanced by increasing the levels of abstraction involved in the representation of a design. The goal of the first level – the basic curvilinear shape – was to represent the underlying structure of a design. This was accomplished by representing the elements of the chair as lines. The goal of the second level was to provide a description of this structure using the smallest possible number of elements. It was defined by translating the 'basic curvilinear shape' into a 'basic rectilinear shape'. The definition of a higher level of abstraction provided a coherent and clear systematisation method for describing complex shapes.

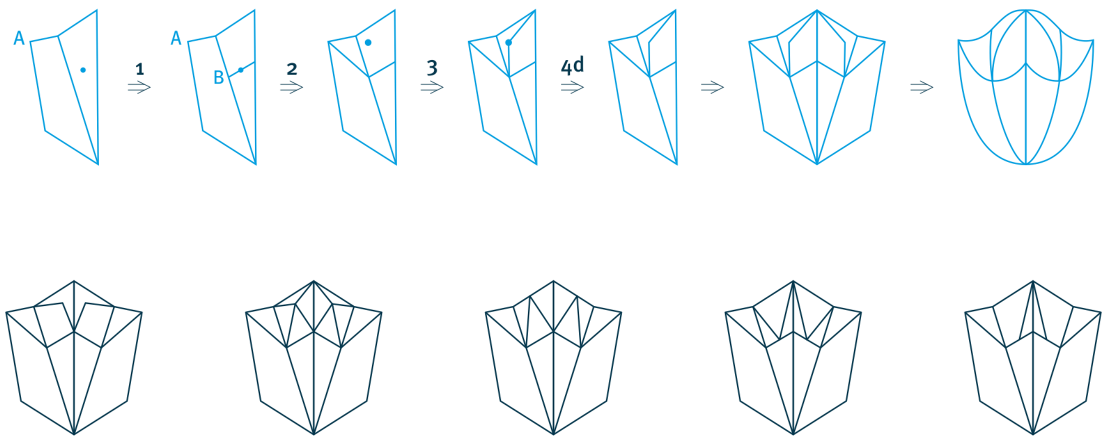


Figure 15. Derivation of a design by rule application: different designs generated by the Hepplewhite grammar (adapted from Knight, 1980)

2.2.2.6. Other Product Design Applications

In his review of the application of artificial intelligence techniques to mass customisation, Simpson (2004) reported on the success of shape grammars in automating generative procedures in the context of product design. Shape grammars can be used as the basis of the methodology for encoding the technological model of a product family architecture (Section 2.1.3.3). In accordance with the model of Pahl et al. (2007, p. 130), shape grammars have been developed as a method to formalise the activities performed in the conceptual design and the embodiment design phases. In addition to the Hepplewhite grammar, there are several examples of the application of shape grammars in product design.

The coffeemaker grammar (Agarwal & Cagan, 1998) employs the additive strategy to develop the design language. The overall shape of the coffeemaker is divided into three units, and different sets of rules are applied separately to each unit. Labels control the functional requirements and precede the application of rules for shape generation. The initial grammar was extended to include manufacturing costs within its properties (Agarwal et al., 1999). The cost information serves as an evaluation criterion of the customised design. The evaluation criterion supports the final activities of the embodiment design phase, by improving a preliminary layout into a definitive layout.

The motorcycle grammar (Pugliese & Cagan, 2002) is a more generic grammar comprising a two-dimensional side representation. Besides the generation of different motorcycles, it encompasses a set of rules that enables the generation of solutions in a specific style, namely a classic Harley-Davidson. The front view of Buick vehicles (McCormack et al., 2004) is a specific grammar developed to explain a particular design style. The cross-over vehicle grammar (Orsborn et al., 2006) also applies the shape grammar formalism to generate vehicles, but is built upon a different approach. It analyses a sample of automobiles, which are categorised into three classes. The grammar operates in front, side, and rear view representations, and it enables the generation of crossover vehicles by a novel combination of shapes. Considering the support for the design process, these grammars codify the 'principle solution' – the first step of the embodiment design phase in the model of Pahl et al. (2007) – into a design space by addressing functional requirements during shape generation. They enable a better support of the initial steps of the embodiment design phase permitting the generation of preliminary layouts. However, they exclude issues related to three-dimensional representation and material properties.

The application of shape grammars in other industrial design examples confirms its suitability to codify the characteristics of a style and assist designers in the process of form finding (Table 1).

2.2.2.7. Evaluation

Evaluation is an assessment mechanism that is developed to take given criteria into account in the process of generation. Its combined use with shape grammars can be summarised by two main categories: syntactic and semantic. In the syntactic category, evaluation is (mainly) based on the required performance, such as cost or structural issues. In the semantic category, evaluation is based on a set of characteristics defined to interpret the generated designs.

Cagan (2001) discusses the integration of evaluation with shape grammars, arguing that, depending on the goal of the shape grammar, evaluation can be incorporated in the shape grammars' properties or postponed to after exploration of the solution space.

Cagan and Mitchell (1993) pioneered the automated search for designs using shape grammars by creating shape annealing. This optimisation technique combines a simulated annealing algorithm (Kirkpatrick et al., 1983) with the shape grammar formalism to control rule application based on functional requirements. The concept was further developed by Shea and Cagan (1999) to generate and optimise the configuration of trusses, based on topology and structural optimisation. The algorithm searches for optimal designs based on structural conditions, by manipulating rules in a model with a high level of abstraction. In this approach, the grammar is responsible for the generation of the geometry, while the annealing algorithm optimises designs according to structural performance requirements, which comprise both syntactic and semantic goals. The procedure starts with the FEM analysis of an initial design. This model is then submitted to optimisation. The shape annealing algorithm applies a shape grammar rule creating a new iterative stage which is evaluated against the goals. A probabilistic routine estimates the degree of conformance to the goals and evaluates the existence of a better design to assess whether it accepts the solution or continues the search. Shape annealing permits the codification of the conceptual design and embodiment design phases of the design process, thus permitting the generation of a definitive layout. This method supports the designer by presenting alternative solutions that include performance requirements (Figure 16). The resulting design must be detailed in order to be produced. The principles were applied to different topology problems involving the design of civil structures (Shea et al., 2005; Shea & Smith, 2006).

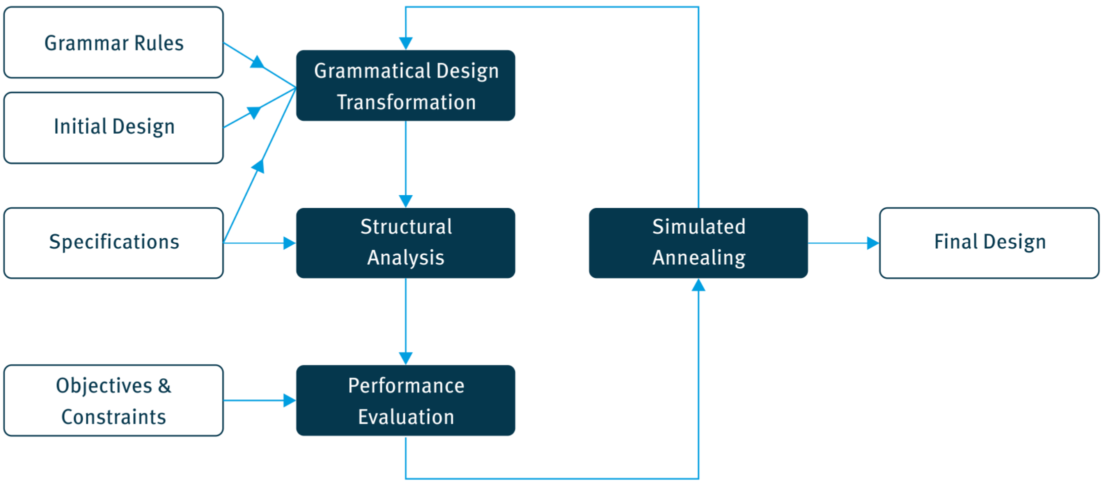


Figure 16. Shape annealing overview (adapted from Shea & Cagan, 1999, p. 243)

Evaluation focusing only on semantic goals is identified in the work of Hsiao and Chen (1997). After morphological analysis, the authors construct a system to generate preliminary layouts of office chairs. Then, the shape grammar codifies semantic properties that can be applied to chair components after the preliminary layout is defined, in order to detail shape-related aspects. Lee & Tang (2004) applied the semantic approach in the development of a genetic algorithm that transforms the shapes of digital cameras based on an evaluation mechanism that included the user. The genetic algorithm supports design exploration after a preliminary layout is defined. Therefore, the generation of alternatives is based on a model with a lower level of abstraction that represents the shapes of the final design.

2.2.2.8. Computer Implementations

"Shape grammars naturally lend themselves to computer implementations: the computer handles the bookkeeping tasks (the representation and computation of shapes, rules, and grammars, and the presentation of correct design alternatives) and the designer specifies, explores, develops design languages, and selects alternatives" (Tapia, 1999, p. 59).

The intrinsic computational principles of shape grammars determine the goal of the computer implementation. Although shape grammar interpreters (Chau et al., 2004) have been developed in research projects, there are many issues regarding this subject. According to the current state of the art in shape grammars, Tapia's premises were never fully resolved in a shape grammar interpreter. The representation of different algebras, embedding and shape emergence, parametric properties, curvilinear representation, three-dimensional shapes, different levels of abstraction and usability of rules are some of the issues that have been tackled in the development of interpreters and can be grouped under the broad categories of representation, computation, and graphic user interface.

Gips (1999, p. 5) identified the different competences needed to 'develop' and to 'implement' a shape grammar by affirming that developing a shape grammar require visual thinking, while implementing it as software require symbolic thinking. In addition, the author claimed that the graphic user interface in shape grammar interpreters is one of the most crucial issues, since it does not fully address the identified different competences. The graphic user interface problem is also addressed in Knight (2000), when she states that there are no graphic user interfaces suitable for non-programmers.

Gips also conceptualised a shape grammar interpreter as a plug-in for traditional CAD software used to assist the design process to overcome the barrier of what he defined as "proof-of-concept implementations." A prototype of Gips' concept was developed by Frank Hoisl (2012). Spapper (Hoisl, 2013) is an open source plug-in for FreeCAD (2014) that supports the construction of three-dimensional shapes based on parameterised primitives and enables rules to be defined and applied automatically. It resolved some issues observed in the literature, such as three-dimensional representation, Boolean operations, the use of labels and a friendly user-interface[5] for non-programmers. It was envisaged that the approach could be supplemented with simulation tools and manufacturing capabilities to provide a valid support for the design process (2012, p. 95). Nevertheless, the current state of the art does not provide any shape grammar interpreter with the capacity to support an integrated design process ranging from concept to manufacturing.

[5] Friendly user interface is considered here on the basis of Hoisl' thesis results and from direct experimentation with the software in August 2011.

2.2.3. Parametric Design Models

“ ‘This is the shape I have sketched, but how do I formally describe it’ versus ‘This is the formal shape description system I am using, how do I harness and control this system to create the shape I like’ ” (Aish, 2005, p. 10).

Feature-based modelling, constraint modelling, associative geometry and parametric modelling are terms that describe a common standard practice enabled by CAD mechanical design systems. This flexible procedure encompasses the definition of a geometrical model as a set of different geometrical entities described by dimensions and constraints. These features enable a single dimensional change to coordinate the modification of the whole geometry (Light & Gossard, 1982). The underlying concepts of relation and change coordination evolved from a CAD technique used in the fields of industrial design and mechanical engineering into a design strategy – parametric design – first defined in architectural design (Monedero, 1997; Burry & Murray, 1997). This section discusses the differences between terms often used to describe similar concepts.

2.2.3.1. Parametric Software

Parametric software[6] can be divided into two major groups: feature-based and graph-based.

Pro/Engineer, released in 1988, was the first software package with associative feature-based modelling capabilities (PTC, 2014). Together with CATIA and NX, this high-end multi-platform software was widely used in the aerospace, automotive and shipbuilding industries. In addition to CAD capabilities, these software packages offered integrated CAE and CAM modules addressing Product Lifecycle Management (PLM), which allowed for the complete definition of a product development process. Feature-based modelling became more widespread in the product design industries after 1995. SolidWorks, launched in 1995 (Bowd, 2004), created the market for similar lower-end applications, especially developed for PCs rather than UNIX workstations. In this type of parametric software, the three-dimensional model is constructed by defining features and geometric relationships between elements. Features and relations are recorded and automatically maintained in a hierarchical tree structure (Shah & Mäntyla, 1995, p. 67). This condition is the basis of design flexibility, since it allows for access and manipulation of properties throughout the design process. Three-dimensional models can be refined by updating the constructs rather than redesigning them.

Graph-based modelling software was initially developed for architectural design (Aish, 2003). Generative Components was commercially launched in 2007 (Bentley Systems, 2007), the same year the Grasshopper plug-in for Rhinoceros was released. Graph-based modelling allows

[6] There are parametric capabilities in 3D computer graphics software for animation, such as stack-based modifiers in 3D Studio Max or graph representation in Houdini. However the literature review focuses on software particularly suited to industrial design processes.

designers to define elements of parametric design using a visual programming language, in a GUI decoupled from the CAD representation space. The algorithmic construction of the digital model is made explicit by encoding constraint expressions or rules in the graph-based editor (Woodbury, 2010, p. 35).

Textual programming (or scripting) is a complementary approach to parametric software which is common to both feature-based and graph-based modelling (Woodbury, 2010, p. 35). Users are able to customise software default functions to meet their particular needs via the application programming interfaces (API) that exist in CAD software. Textual programming provides a precise means for the exact definition of activities performed by the computer and for making the design rationale explicit (Mitchell et al., 1987, p. 109). This type of approach provides greater control over the execution of tasks and requires a higher level of abstraction in setting up design specifications. However, it requires a new type of – symbolic – literacy that is often beyond the scope of traditional product designer foundation skills.

2.2.3.2. Parametric Models

Parametric models are defined in the literature both as parametric modelling (Davis, 2013; Woodbury, 2010; Aish & Woodbury, 2005) and parametric design (Roller, 1991; Monedero, 1997; Burry & Murray, 1997; Aish, 2005; Hernandez, 2006). These terms aim to describe the process of defining and editing relations in parametric models with the aid of CAD-based techniques. Moreover, they are terms which encompass the design thinking involved in defining the reconfigurable schema encoded in computer software. Accordingly, parametric modelling and parametric design are often used to characterise the 'how' and 'what' of design activity which uses parametric models.

A parametric model is a geometrical CAD representation that accommodates dynamic change by varying the numerical values of one or more parameters, i.e. the variables (Burry & Murray, 1997). The geometrical model becomes defined as a reconfigurable set of algorithmic relations in which the designer defines a schema containing the relations between the elements and sets of elements of the object (Woodbury, 2010; Davis, 2013, p. 31). Varying the parameter values creates a different configuration or variant, generated from a single parametric model.

Monedero (1997) identified two types of constraints: geometrical and physical. Geometrical constraints refer to relationships between elements, such as perpendicularity, tangency, or parallelism. Physical constraints are based on CAE definition, by variables such as pressure or weight. These types of constraints can be expressed as explicit values, mathematical equations, or scripts that describe relationships between elements. In this definition, a parametric model can be interpreted as a central interactive model with reconfiguration capability. The ability to contain both geometrical and physical information provides for multiple uses throughout the design process, since it contains information for "conception, simulation, analysis, presentation, detailing and construction" (Malé-Alemany & Sousa, 2003, p.5).

Monedero characterised the assessment of constraints and degrees of freedom as important activities in the definition of relations in a parametric model. Degree of freedom is a direct product of the relationships between constraints in a parametric model encoded in feature-based software. Geometrical and dimensional constraints must be consistent whenever a new variant is produced. Therefore, the relationships between dependent and independent variables must be assessed in order to maintain the level of consistency throughout the generation of different variants. The assessment of constraints defines the potential for reconfiguration without creating inconsistencies between parameters. Burry and Murray (1997) also indicated that the designer must consider the appropriate level of flexibility when constructing a parametric model. Consequently, estimation of use must be planned in advance by considering a trade-off between the amount of control and the number of explicit parameters needed to describe the reconfigurable geometry.

Planning, creating and editing relationships becomes the central activities in designing with parametric models (Woodbury, 2010, p.24). The author identified these activities as the major differences in designing with parametric models when compared with designing with conventional design tools. When designing with parametric models the designer does not create a single solution by direct manipulation of the geometry. Rather, the designer establishes the relationships, thereby enabling the generation and exploration of multiple solutions by using the software.

2.2.3.3. Parametric Design *versus* Parametric Modelling

Parametric modelling requires a designer skilled in geometry, composition, and algorithmic thought (Aish, 2005). 'Geometry' is the central issue in the creation of parametric models (Woodbury, 2010, p. 81). Management of geometric relationships during reconfigurations and the creation of an auxiliary geometry that controls the position and stability of frontend geometry are key design abilities. 'Composition' skills are used to organise and coordinate dynamic topological relations between the elements and sub-elements that create the final design. 'Algorithmic thought' is the capacity to state design intentions in a computable manner, so that the designer is able to control the constructs of generated solutions using parametric software.

Woodbury (2010, p. 35) summarises the set of technical skills as follows:

"Conceiving data flow; dividing to conquer; naming; and thinking abstractly, mathematically and algorithmically form the base for designers to build their parametric craft."

This type of design thinking characterises parametric modelling activity. Instead of designing a single configuration, a designer must anticipate the general schema that will generate multiple configurations (Vanucci, 2008). These skills are developed to handle computational tools more effectively. However, they are not solely dependent on software handling but also include the preceding strategy that conceptualises the design intent with an implicit design endeavour for variation. Monedero considered this type of reasoning in his 1997 paper. The author specified the notion of family as an important feature for parametric design. A family of designs comprises the topological description between the constituent parts and their dimensional constraints. The designer characterises a family as a general envelope capable of generating multiple outputs. This design intention becomes formally 'represented' in a parametric model.

Monedero's concept of family resembles some aspects of Bonsiepe's characterisation of formal synthesis in industrial design. Bonsiepe (1992 [1975], p. 221–224) defined this design method as the one used to define the principles required to achieve aesthetic coherence across different components of a single product, or across products in a product family. He classified relations of similarity under several classes, each corresponding to a progressive level of conformance. Bonsiepe specified three main classes that were important in industrial design. The first refers to deformation of a single element under a fixed schema. The second is the repetition of an element or feature among different components or across different products to achieve identity. The third is the relationship between different elements within a variation schema or structural skeleton (Arnheim, 2004 [1954], p. 13) such as a grid, in order to create balance.

The type of reasoning described in the previous paragraphs is not related exclusively to the technological use of parametric modelling. Prior conceptualisation of the variation schema relates to design methods. Therefore, in the remainder of this thesis, the term 'parametric design' is used to describe this type of reasoning. It is the methodology for designing an artefact in such a way that it possesses an inherent construct mechanism capable of producing different parametric variants.

As mentioned previously, the terms parametric modelling and parametric design are often used to describe both design thinking and CAD-based techniques. This misuse of terms leads to difficulties in classifying digital design practice. As Davis observed (2013, p. 30–31), even individuals provide different definitions at different points in their careers.

In support of the argument that parametric modelling and parametric design are different conceptualisations although they share some overlapping territories, the Oxford dictionary provides the following definitions (2014a, 2014b):

"Design: A plan or drawing produced to show the look and function or workings of a building, garment, or other object before it is made."
"Modelling: The activity of making three-dimensional models."
According to these definitions, 'modelling' can be characterised as a sub-set of 'design' activity. Modelling enables a parametric model to be constructed, which embodies parametric design. Parametric modelling is the set of CAD-based techniques that define a parametric model ('how'.) Parametric design is the design method employed beforehand to guide the process of designing a general schema capable of generating multiple solutions ('why'.)

According to the literature, a parametric model is a smart CAD model that accommodates dynamic change by variations in parameters. There is no distinction between a conventional representation produced with feature-based software, and thus parametric, and a representation made to create dynamic change that reflects a specific design endeavour. Therefore, a more comprehensive definition should distinguish between 'parametric models' and 'parametric design models'.

2.2.3.4. Parametric Design as a Complementary Method

These premises indicate that parametric design can be coupled with specific design methods and can therefore be considered a complementary generative design method that combines a design method with the reasoning derived from CAD-based techniques. Using Artificial Intelligence (AI) terminology, it can be hypothesized that parametric design is a soft-generative design mechanism, as opposed to a strong-generative design mechanism.

Oxman (2006) categorised parametric design as a sub-class of digital formation models, which means that it is a computational technique rather than a generative design method. Digital formation models encompass a dynamic concept of representation enabled by digital design tools. They differ from static representation in the way in which they allow for non-deterministic design processes. Nevertheless, the focus is on the geometrical aspects of the designs. Accordingly, parametric design does not provide an explanation of the generative mechanism on the same level as shape grammars or evolutionary models.

Ipek Dino (2012, p. 208) starts from the same principle, declaring that generative design methods require specification of the formation process of the design. However, unlike Oxman, Dino classifies parametric design as the third class of generative models, pairing it up with shape grammars and evolutionary models. Although Dino presents this argument, she does not discuss it by mapping out direct differences or complementarities with shape grammars or evolutionary models. She emphasizes the importance of parametric design in design exploration and algorithmic thinking within the generative models, but does not explain how the algorithmic construct and manipulation are established before implementation. The author (2012, p. 209) summarises the requirements of a generative model into four principles: establishment of the starting conditions and definition of the parameters; establishment of the rules to guide the generation; the ability to generate variants; and the selection of the fittest variant according to a predetermined goal.

The first two principles of Dino's argument are not totally explained in parametric design. Following the premise of the complementary generative design method, a case is now presented in which parametric design can be coupled with another design method to strengthen its generation capabilities.

Systematic design, a design method developed by Christopher Jones in 1963, can be coupled with parametric design, therefore guiding the strategy of designing for variation. The goal of systematic design is to develop a range of solutions for a given specification. In addition, it provides the means to clarify the reasons whether or not each solution may satisfy the specification (Jones, 1984, p. 24–25). Systematic design combines logical analysis with creative thinking aimed at developing a range of solutions and partial solutions from a set of specifications and sub-specifications, respectively. Jones's method comprises analysis, synthesis, and evaluation stages, each defined by a set of procedural steps. 'Analysis' encompasses the definition of design requirements and the determination of performance specifications. 'Synthesis' is the concept generation stage, in which solutions are developed to solve individual performance specifications. Different design solutions are developed through creative thinking.

Partial solutions are developed independently in order to produce several combined solutions, a principle shared with modularity (Ulrich & Tung, 1991). The refinement procedure includes the definition of limits, i.e. the planning of the variation space for the range of dimensions, shapes, and materials. All the procedures are executed according to specific performance specifications. The last stage of the method is the 'evaluation' stage, in which alternative solutions are confronted with performance requirements in order to assess the level of fulfilment.

Parametric design can follow the stages of systematic design to guide the variation schema and respective details, thus establishing itself as a complementary generative design method. In such cases, parametric modelling is employed as the implementation technique for subjects related to the 'synthesis' stage, while performance-based tools support the 'evaluation' stage by simulating real-world conditions (Section 2.2.4).

Therefore, by linking parametric design to other design methods, it becomes possible to develop specific generative design methods to design for variation. The artefact is a schema or a collection of interchangeable components described by variation schemas that can be encoded in parametric software. Complementary methods may guide parametric design and strengthen its foundations as a generative design method. The definition of a design as a schema instead of a unique solution creates levels of complexity in the design process.

2.2.3.5. Levels of Indirection

"In this way we should view computational design as part of a normal progression in which the designer and the artefact are separated by an increasing number of levels of indirection, that in turn introduce higher levels of expression and control" (Aish, 2005, p. 11).

This statement by Aish indicates two apparently contradictory terms: indirection and control. Before discussing these issues, two overlapping domains must be outlined. 'Indirection' emerges from the definition of a 'meta-artefact' instead of a unique solution. This issue relates to parametric design and the encoding procedures in parametric models. 'Control' derives from the use of parametric models which, in turn, derives from the strategy defined by parametric design.

'Indirection' can be explained through an adaptation of Alexander's models (1973 [1964], p. 76), visualised in the Figure 17. The models were originally developed to enable the designer to cope with additional variables and information by increasing the abstraction level. In the original first model, which comprises two levels, the first level represents the actual world and the second level represents the mental picture of the world. The designer is able to cope with additional information by creating a formal picture of the mental picture, embodied as the third level in the second model.

In the proposed adaptation, the first model represents interaction in a traditional CAD representation. The designer directly represents the physical artefact that is the product of his/her design intention and the computer is used as a representation medium.

In the second model, the designer develops a rationale for the design intention, hence a parametric design. The rationale determines how the representation will be encoded. This new level embodies Aish's principle of an "increasing number of levels of indirection."

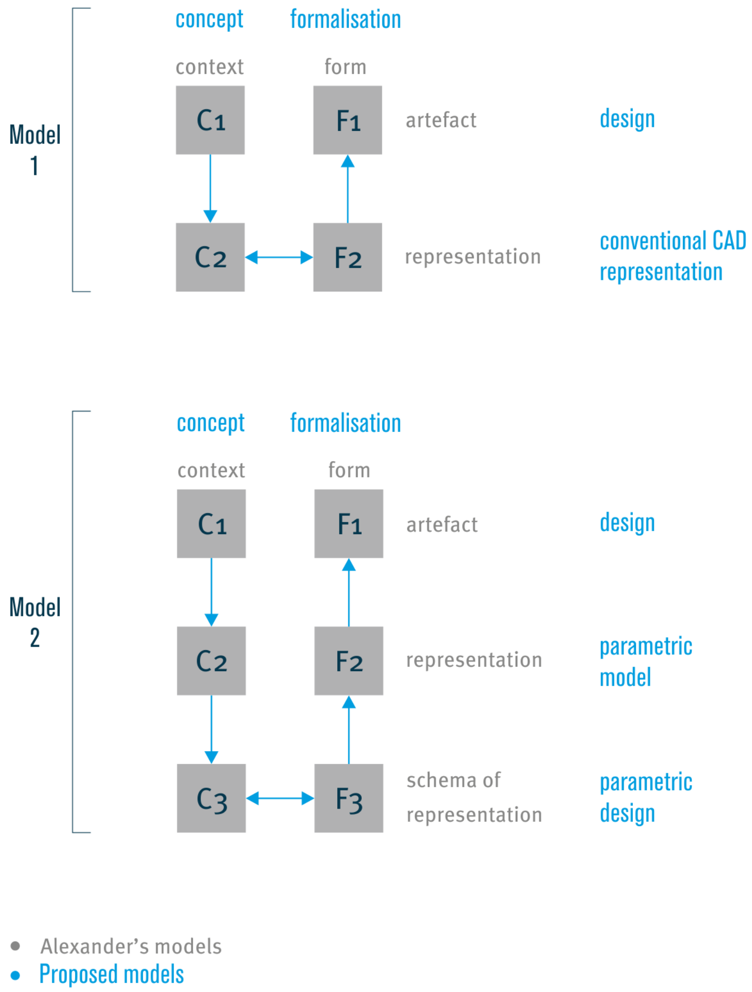


Figure 17. Levels of indirection created in parametric design (adapted from Alexander, 1973, p.76)

A higher level of expression is achieved by the potential to use computational tools to support design generation, rather than using them only for representation purposes. This level of indirection creates the need for additional representations of the design. Researchers who have studied the design process with the use of parametric models confirm this assumption.

“The geometric model at the center of design representation may be slowly fading and should be augmented by generative descriptions of the design processes” (Kilian, 2006, p. 314).

Alex Kilian (2006) investigated how constraint modelling could support design exploration. His experiments focused on four types of constraints (2006, p. 60): functional, topological, geometrical and quantitative. Kilian concluded that computer-based geometrical representation alone was not suitable for representing the cross-dependencies of a design domain (2006, p. 299) and developed multiple representations to support better design variables’ mapping and provide guidance throughout the design process. The change between abstraction levels in the problem facilitated design exploration. Hudson (2010, p. 243) reiterates Kilian’s premises, stating that multiple representations facilitate design documentation and information sharing.

There is an intrinsic complexity to the act of designing with the support of parametric models in comparison to designing with traditional CAD-based tools. This occurs in two major domains: in relation to the designed artefact[7] and in relation to tools.

The literature contains little in terms of exemplifying or discussing the process of translating design specifications into parametric design and the process of encoding them through parametric modelling.

In parametric models, representation is a system of interrelated elements that requires prior conceptualisation and formalisation of the designed object as a whole. On an operational level, editing relationships instead of direct elements becomes a part of design activity (Woodbury, 2010, p. 24–25). The object becomes a schema or, in other words, an explicit formalisation of the design rationale, and the prediction of geometric change and coordinated reconfiguration of components therefore becomes part of the design activity. However, this may lead to difficulties associated with a higher number of variables involved in the design activity.

Aish and Woodbury (2005, p. 151) recall the additional effort of using parametric models, which is related to planning (parametric design) and local design decisions (parametric modelling.) The need to plan before encoding parametric models is an important activity in comparison to traditional CAD modelling. The designer must anticipate the parameters and the hierarchy of dependencies in order to establish the design space for variants (Davis, 2013, p. 39). Anticipation of the design space challenges the effectiveness of parametric models in the early conceptual steps of the design process. This issue directly relates to the encoding procedures for parametric models. The modelling strategy depends on the results expected from the model, the intrinsic conditions of the design, and user experience. The level of constraint and the interdependency across parameters define the level of flexibility accommodated in a parametric model (Kilian, 2006; Davis, 2013; Hudson, 2010).

A parametric model’s usability depends on the number of parameters, which provide the instrumental capability to reconfiguration. Killian (2006, p.110) observes that there must be a

[7] The discussion focuses on the act of designing and not on the end result. Although complex shapes have been a common output of parametric models and the term ‘parametericism’ has been used to describe the design style, the subject is beyond the scope of this thesis.

correct trade-off between the number of parameters and the envisaged usability of the parametric model, since a high number of parameters decrease the intuitive use of parametric model during design activity.

The flexibility of parametric models depends on the number of parameters and the schema that guides the implementation procedures. Several authors recall the difficulties associated with changing a schema. Davis (2013, p.42-43) reports several examples in the literature and in practice where starting a new parametric model instead of refining an existing one is the prevalent strategy when major changes occur in the schema.

Hudson (2010, p.240) proposes an iterative encoding process. In the first iteration, the parametric modelling tests the validity of the schema's modelling strategy, functionality of parameters, and relations. The second iteration acts on the previous information and, whereas the parametric design can be refined, parametric models are rebuilt from scratch. These subjects are related to an intrinsic issue, namely time investment.

"(...) parametric models are definite, complex structures that take time to create. Too often, they are not quick" (Woodbury, 2010, p.36).

2.2.3.6. Discussion

Parametric software assists the design process, from concept generation to manufacture detailing. The three modes of parametric modelling presented enable different design methods to be established. Feature-based modelling is well established in industrial design practice. This type of parametric software encompasses integrated CAE and CAM tools and accurate geometric modelling kernels, due to requirements from industries such as the automobile and aeronautical industries.

Graph-based modelling provides a higher level of abstraction in comparison with feature-based GUI. This derives from the ability to decouple parametric design from parametric modelling within software usage. The Rhinoceros and Grasshopper visual programming interfaces have been widely adopted, both in the architectural and the design community, at academic and professional levels. Community bottom-up approaches leverage the traditional top-down approaches associated with the development of tools for specialist groups of users, phases of the design process or industries. This has led to a major expansion of plug-ins that extend parametric capabilities (McNeel & Associates, 2014). However, Rhinoceros does not support feature-based modelling, which implies rebuilding the model until the final configuration is achieved (Vanucci, 2008, p. 123).

Textual programming provides the highest level of abstraction and means to control all the features of the design intention, at least theoretically.

Other design methods can supplement parametric design in order to improve the description of the 'meta-artefact' as a variation schema. Multiple representations of the design intention facilitate the parametric design modelling.

The implementation and use of parametric design models require experimentation, testing, and refinement, which are time-consuming activities. The generation of multiple instances from a unique model may compensate for the time invested in this activity. Another possibility involves establishing parametric design models as repositories of information to guide performance-based models and CAM procedures. This latter situation was envisaged in Monedero's definition of parametric design, Oxman's models and Menges's practice. These practices support an extension of the design activity using computer-aided design from mere representation to include the establishment of generative design systems (Oxman, 2006, p.253).

2.2.4. Performance-Based Models

"Generative design methods are capable of generating concepts and stimulating solutions based on robust and rigorous models of design conditions, design languages and design performance" (Shea et al., 2005, p. 533).

Time investment is one of the disadvantages of developing parametric models observed in the literature. The return on time investment comes not only from the usability of the model in terms of generating multiple variants, but also from the information that can be used to support the subsequent steps and phases of the design process. The use of parametric models to mediate in the relationship between the design and engineering disciplines allows for integrative approaches (Holzer et al., 2005; Gujarathi & Ma, 2011). The link between parametric models and optimisation tools enables design exploration to take place in collaborative and hybrid territories that transcend the traditional professional boundaries (Oxman & Oxman, 2010). Performance-driven generative design tools (Shea et al., 2005) require the definition of both geometry and performance constraints. This enables the exchange of information between these modules to generate solutions optimised to real-world conditions resulting from simulations performed on digital tools.

There are two types of use of performance-based parametric models (Oxman, 2006; Dino, 2012): a) to generate solutions that meet the performance criteria; b) to perform automatic searches in a solution space. These two types of performative principles involve different approaches. The former is a static approach, in which parametric models are limited to generating a sub-set of workable solutions based on performance requirements. The latter is a dynamic process characterised by the use of computational tools in the search for optimal solutions.

From the literature, it is possible to determine a third type related to performance-based parametric models, namely computational synthesis[8]. The computational synthesis field is broader than optimisation and parametric models (Cagan et al., 2005) and is a method suited to the domains of representation, generation, evaluation and guidance, allowing for greater interaction between modules and additional control through textual programming. AI techniques support the handling of complex constraints and interdependencies across the modules. The developers of the system may fine-tune the entire system, either by rewriting algorithms or redefining the problem definition in each module. Moreover, it becomes possible to address multi-objective problems without simplifying them into single objective functions. This approach relates more to tool development than tool usage alone.

2.2.4.1. Optimisation

"The kinds of problem that designers tackle are regarded as ill-defined or ill-structured, in contrast to well-defined or well-structured problems such as chess-playing, crossword puzzles or standard calculations. Well-defined problems have a clear goal, often one correct answer, and rules or known ways of proceeding that will generate an answer" (Cross, 2000 [1989], p. 14).

From a problem-solving perspective, there is a gradual progression from ill-defined problems to well-defined ones throughout the design process. When the design solution is detailed for production there is a need to re-check technical feasibility (Pahl and Beitz cited in Cross, 2000, p. 38). During these last steps of the embodiment design phase, interdisciplinary collaboration between design and engineering refines the product based on analysis and verification supported by experimentation. Although nowadays the activities to define this working step – definitive layout – are supported by computer-based analysis methods such as FEM (Christensen & Klarbring, 2009, p. 2), the approach remains iterative-intuitive, since a series of refinements are executed manually.

Optimisation is conceptually different from the iterative-intuitive approach. The problem must be formulated in mathematical terms and there is an almost automatic[9] search for the best solution within a predefined set of constraints (Burry & Burry, 2012, p. 117). Arora (2004 [1989], p. 5) affirms that the "rigorous formulation of the design problem helps the designer gain a better understanding of the problem." The formulation of an optimisation problem must follow a series of steps (Arora, 2004, p. 15):

"Step 1: Project/problem statement.
Step 2: Data and information collection.

[8] Computational design synthesis is not related directly to this research. It was referred to because it focuses, from an AI perspective, on the parts of the generative design system developed in this thesis. Cagan et al. (2005) and Chakrabarti et al. (2011) review the state of the art and the applications in this field.

[9] The expression 'almost automatic' follows Christiansen and Klarbring (2009, p. 3) 'much more automatic' expression when comparing it to the iterative-intuitive approach. The goal is to eliminate the assumption that the procedures do not require human control when the problem formulation, constraining, selection of algorithms and related considerations of the process are defined by the designer.

Step 3: Identification/definition of design variables.

Step 4: Identification of a criterion to be optimized.

Step 5: Identification of constraints."

The first step requires clarification of the goal, often through a descriptive statement. In the case of structural optimisation, the second step involves analysis of design instances to gather information about stress, displacement, and geometry. Related data, such as material properties and performance requirements, are identified during this step. The third step relates directly to parametric models, since the parameters defined can be identified as design variables for an optimisation problem. The variables are the numerical description of the initial state of the design to be optimised. The objective function[10] is defined in the fourth step and can be expressed in order to be minimised or maximised. The final step in the formulation process is the identification of constraints to define the solution space in which the optimisation algorithm will search for the optimal solution.

2.2.4.2. Optimisation Algorithms

The search for the objective function is performed by an optimisation algorithm. This procedure generates and evaluates multiple instances to find the optimal solution. Optimisation algorithms can be divided into two groups: deterministic and probabilistic.

Deterministic or direct search algorithms (Lewis et al., 2000) were the first to be used in computation. They are often used as exploratory algorithms or for local optimisation when there is a clear insight into the nature of the variables. Heuristics divide the problem into sub-problems and each iteration determines the criterion for finding the next state.

Probabilistic algorithms are used in problems when there are uncertainties in the elements, the search space or the path for solutions. In this class of algorithms, the probabilistic component is included in the routine so that the current state does not determine any other state. These algorithms do not guarantee the best global solution but an adequate trade-off between time and the effectiveness of the solution. These principles make them suitable for structural optimisation problems (Arora, 2004).

Simulated annealing is one of the most widely used algorithms in structural optimisation problems. Simulated annealing is a stochastic optimisation method analogous to the annealing of metals in statistical mechanics (Kirkpatrick et al., 1983). Annealing is a process in which melted metal is slowly cooled to solidify in its minimum energy state. Temperature is the gradient variable that stabilises the system in each state and determines the approach to find the next step. The search routine in the simulated annealing algorithm comprises a degree of randomness that also involves comparison with the energy of the system in the previous state.

[10] When the goal of an optimisation problem is declared by two or more objective functions it is called multi-objective optimisation (Arora, 2004, p. 17). This class of optimisation is beyond the scope of this research.

If the next state is suitable, it will be accepted, otherwise the previous state is retained and a new iteration begins in order to find another state. Iteration stops when the energy of the system reaches a local minimum configuration. Due to these characteristics, this optimisation technique is suitable for combinatorial and non-linear problems with several constraints.

2.2.4.3. Structural Optimisation

Structural optimisation is the sub-set of optimisation problems that considers issues related to mechanical behaviour during load bearing (Christensen & Klarbring, 2009, p. 1). Objective functions often measure weight, stress or displacement, while design variables express the geometric parameters to be changed during the process. There are three types of structural optimisation problems which relate to different geometrical features of a design (Christensen & Klarbring, 2009, p. 5–6). 'Sizing' refers to the thickness optimisation of components, 'shape' to the geometric aspect of the design, and 'topology' to changes that require the addition or removal of components, leading to a new configuration of the design solution.

2.2.4.4. Discussion

Integrating parametric models with optimisation tools is an integrative approach to generative design. Functional requirements, such as structural behaviour and materialisation restrictions, become part of the generation process, contributing to both evaluation and dynamic change in the model, according to the simulation results. This creates a conceptually different approach to the design process, since the conventional post-rationalisation that occurs in subsequent phases of the design process is included in the developed design system (Oxman & Oxman, 2010, p. 17).

Integrating geometric parameters, analysis and optimisation of the design under a specific set of conditions makes the design process more robust. The definition of performative parametric models involves multi-disciplinary thinking, a condition that fosters collaboration between design and engineering, requiring greater flexibility in both disciplines and respective professional practices (Holzer et al., 2005).

Rivka and Robert Oxman (2010, p. 15) observe that assimilation of these tools may reverse the traditional process of product development so that it becomes "material, structure, form."

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2.3. Chair Design

This section analyses the chair as the chosen typology for research in the product design field. This typology embodies multiple design variables, involving design methodology, technological feasibility, and user considerations. Transformations in chair design processes are contextualised, based on the interlinked relationship between experimentation and technological development, to support the approach taken in this research.

The section begins by presenting the chair as the typology for experimentation. This premise is mapped by presenting groundbreaking examples associated with different aspects of the product development process. The goal is to support the principle that changes in methodology, tools or production processes provide an opportunity to develop the furniture design field.

2.3.1. The Multiple Dimensions of the Chair

A chair is a separate seat for one person, typically with a back and four legs (Oxford Dictionaries, 2014). Occasionally, it may have arms. It supports a human body in a sitting position through a combination of three requirements: supporting the thighs on the seat, supporting the lumbar region at the back, and enabling the feet to rest on the ground. On an operational level, this involves unloading the weight of the torso and head to the pelvis and hips (Fiell & Fiell, 2001). This support must be strong enough to bear the weight of the body without failure and be resistant to long-time use.

The sitting position allows for a set of functional interactions with other people, artefacts and spaces, meaning that chairs may be designed for specific contexts or activities, a particular seating period, a set of different users, or a specific user. A chair must suit both the physical and the psychological conditions of the user, as well as the performance conditions for the context in which it is used.

A chair can be the result of either an industrial or artisanal process, or even a combination of both. Moreover, it can be developed by a single designer or combine input from several professionals, for use in domestic or public spaces. Given all these possibilities, the chair encompasses multiple layers of functional and symbolic meanings and has therefore been studied in several different areas. Historical studies show how its use has evolved from early civilizations, establishing relations between both context and user (Oates, 1981). An alternative historical approach may focus on clarifying the introduction of new materials, industrial processes and technical elements in furniture design, and how this influences new cultural customs (Giedion, 1975 [1948]). Ergonomics determines serviceability requirements for specific postures and contexts, based on anthropometric data (Tilley & Associates, 2001, p. 44). Semiotics and material culture studies can interpret, amongst other features, the social and cultural meaning of a specific chair in a specific context or analyse its value in the construction of a person's identity. These examples indicate that the significance of chairs extends far beyond the sphere of design.

2.3.1.1. Delimitation of Scope

In order to circumscribe the chair within the design field, the framework of analysis is restricted to chairs developed by a specific process which comprises observation of human interactivity and experimentation with methodologies appropriate for the given social, economic, cultural, and technical contexts. This mediation between the poetic expression embedded in design thinking and the pragmatic attitude embodied in design aims to satisfy latent user needs in a specific cultural context through a functional approach.

Chair-making became a specialist activity separated from cabinet-making, joinery or carving in the eighteenth century (Sparke, 1987, p. 21). It followed the principles defined in the pioneering work of Josiah Wedgwood on the division of labour in the pottery industry (Forty, 2005 [1986], p. 32–34). Chippendale's book *The Gentleman and Cabinet-Maker's Director*, published in 1754, embodies several principles of chair design observable in contemporary furniture design. The first concerns the separation of design from manufacturing activity. The manufacturing process involves a series of successive operations to produce individual components in quantity, thus defining the concept of batch production. Distribution and marketing also changed: the book enabled designs to be transmitted to wider geographical areas and showrooms facilitated the acquisition process. The separation of the design, production, distribution, marketing and trading processes still prevails in contemporary furniture design.

Classes of chairs can be defined by the context in which they are used (e.g. office, dining), their enabling function (e.g. rocking, wing, easy) or implicit function (e.g. stacking, folding.) Fiell and Fiell (2001) characterised two broader classes – office and domestic chairs – and a class transversal to both, namely avant-garde chairs.

2.3.1.2. Avant-Garde Chairs

The chair is the main experimentation typology within the product design field because it allows for the study of specific variables in the design process and the creation of a functional statement of a design approach. This represents a synthesis of function, structure, technical feasibility, aesthetics and market interpretation for a particular type of society (Fiell & Fiell, 2001, p. 32). The significance of embodying such values in a chair is that it communicates directly with the user on several operative layers and symbolic dimensions. Avant-garde chairs result from this type of experimentation process, in which designers aim to present their ideology, manufacturing approach, material testing or modus operandi. The goal is to expand the established boundaries defined in the state of the art. Experimentation can be confined to a particular phase or be established across the product development process. The motivation may be to test a new material, new production technique or some other technical innovation, or to respond to latent user needs or explore new aesthetic expressions.

The avant-garde approach is more prevalent in domestic chair design than in office chairs and this is directly related to the fact that office chairs are a more complex type of chair. Office chairs must follow regulatory standards for robustness of construction and ergonomic issues, such as seating time and functional body support. These conditions create a network of interrelated variables which must be resolved by a team of professionals. Furthermore, the production process for office chairs involves components that must be mass-produced, thus demanding a more complex type of design process.

Theoretically, domestic chairs are a less complex type of chair and therefore the conditions exist for incorporating additional variables into the design problem. Mel Byars (2006, p. 9) highlighted the following conditions that were present in his selection of chairs to illustrate innovations in design, technology and materials:

"Easy reconfiguration and customization by end users; Ecological concerns; Computer-numeric-controlled and laser-cutting machinery; Inspiration from origami and nature; Special machinery created for individual production; Low-tech manufacture with high-tech materials; High-tech manufacture with high-tech materials; Complex materials never before employed in the furniture industry; Solutions to diminish various costs."

This research focuses on domestic avant-garde chairs. This class of chair represents the pioneering work of designers, establishing new connections between requirements and the physical expression of the artefact. There are two perspectives to this class of chair, each encompassing multiple approaches. The former focuses on the work of designers operating within the constraints of the market and industrial processes to improve relations in specific stages or across the product development process. The latter identifies practices characterised by greater freedom from functional constraints and is concerned with exploring semiotic expression. Williams (2006, p. 118) characterises this perspective as "furniture-shaped political or social manifestos (...)." This thesis is based on the former approach.

2.3.2. Technology-Driven Experiments

"In fact, bringing new technology into being is a complex process in which goals are discovered, determined and modified along the way. Invention builds on previous invention and is always part of a larger current of technology. It takes time and requires more than one kind of technical effort. It is made up of many different subinventions. Each separate turning of a technical tick, however small, has its own process. And the process of invention continues throughout the life of any new technology" (Schon, 1967, p. 8).

This subsection analyses a set of selected cases of technology-driven experiments in chair design. The goal is to demonstrate that experimentation within a set of technical constraints can trigger innovative approaches. In addition, the product development process must involve close collaboration between designers and producers, sometimes in an open-ended manner that does not end when the product is launched on the market. Continuous refinement in order to achieve the proposed goals is often a thoroughly iterative process.

2.3.2.1. The Panton Chair

When Mart Stam designed the first cantilever chair in 1926 (Máčel, 1990), he created a new archetype that was constantly reworked in chair design. The goal of creating a chair with a continuous line and no rear legs that was capable of providing a spring movement[11] for its user has been attempted many times in the history of design.

Verner Panton combined the goal of designing a cantilever chair with that of developing a single plastic injection moulded chair. The chair was designed in 1960 and was developed for seven years before it was launched on the market (Figure 18).

"Since its market launch in 1967, it has advanced through several production phases. Only since 1999 has it been possible to produce the chair in accordance with its original conception – out of durable, dyed-through plastic with a lustrous matte finish (Vitra, 2013)."

Figure 18. a) Panton chair; b) Working prototype at Vitra (Source: a) Fiell & Fiell, 2001; b) Vitra, 2014).

Name	Panton chair
Designer	Verner Panton (1926-1998)
Manufacturer	Vitra, Switzerland (1967, from 1999)
Development	1960-1967 (Classic version) Until 1999 (Polypropylene version)
Materials	Rigid polyurethane foam with glossy lacquer finish (1967) Polypropylene (1999)
Size (mm)	height 830, width 500, depth 600. Seat height 415. Seat depth 455

[11] Although spring movement was not part of Stam's conceptualisation of the cantilever chair, since Marcel Breuer's chair it has been an established requirement for this class of chairs.

According to Mathias Remmelle (2000), after the initial fibreglass-reinforced polyester prototypes in 1967, the first production version was made in "Baydur, an HR [high resilience] polyurethane foam produced by the Bayer Leverkusen company, and was varnished in seven colors. In 1970 Vitra replaced the costly production technology, which required thirty minutes to produce one piece, with Thermoplast injection molding. Using a dyed granulate Luran-S made by BASF, the edge profiles had to be strengthened and reinforcing ribs placed underneath the seat."

Panton worked for over thirty years until his death to achieve the original goals of injection moulding. Minor geometric variations were defined in order to combine aesthetic expression with structural and production constraints. The 1999 version, made in fibreglass-reinforced polypropylene, overcame the limitations identified in the Luran-S version, which had breakage problems (ICSID, 2010) associated with use over time. This achievement was possible at the time because the use of computational tools allowed for simulation of the stress on the chair to determine possible changes to the chemical structure of the plastic, the thickness of the material, and the shape geometry of the chair. Moreover, mould-flow simulation permitted the parameters of the injection process, such as temperature of the mould, temperature of the plastics, distribution channels and flow of injection, to be understood in advance. Likewise, it allowed for a more efficient estimation of the geometrical modification of the chair during the cooling process.

The 1990s was a decade in which several developments took place in polypropylene injection moulding. Another example is the Air-chair, designed by Jasper Morrison and developed with Magis during the period 1997-1999, which made use of technology originally developed for the automotive industry (Williams, 2006, pp. 92–93). Nevertheless, the 1999 Panton chair was a major achievement and established a landmark in chair design.

2.3.2.2. The Myto Chair

Working with precedents is a common approach to chair design, whether the goal is to demonstrate a better design or production process, apply a new material or design a better formal configuration. The Myto chair (Figure 19), designed by Konstantin Grcic, was based on a similar principle for designing a cantilever plastic chair produced from a single mould. The chair was developed as a marketing application in the field of product design for the Ultradur material developed by BASF (Wilhide, 2010, p. 71). The product development process, which began in June 2006 and lasted until its market launch in April 2008, involved a similar iterative refinement process to the one employed in Panton's 1999 version: shape refinement, fine-tuning of the plastic chemical composition, and mould optimisation. The chair is the optimised result of the combination of design endeavour and production technology development. As an example of this premise, the oblong mesh displays a shape and pattern designed to optimise the flow of plastic during the injection process. In addition, the set of colours are those allowed by temperature-related issues.

Figure 19. a) Myto chair; b) Evolution of geometries (Source: a)Plank, 2014; b) Wilhide, 2010, p. 85).

Name	Myto
Designer	Konstantin Grcic (1965-)
Manufacturer	Plank, Italy (2008)
Development	2006-2008
Materials	BASF Ultradur® High Speed plastic
Size (mm)	height 820, width 510, depth 550. Seat height 450.

Both the Panton and Myto chairs were possible due to the close collaboration between designer and manufacturer. Refinement is a trial and error activity guided by the knowledge of both parties and requires advances in manufacturing capabilities. The design expression becomes the optimised trade-off between shape, material, and production technology.

2.3.2.3. The Solid and the One_Shot.MGX Collections

Rapid prototyping evolved from a prototyping technique, as the name indicates, to the production of life-size objects with the development of the 'Solid' collection. The 'Solid' collection, designed by Patrick Jouin and produced by .MGX by Materialise in 2004 (Figure 20), consisted of two chairs (C1 and C2), a stool (S1) and a table base (T1) produced by stereolithography (Saville, 2006, p. 116). The collection overcame the size limitation presented by the objects, which was directly related to the dimensions of the production machine, by using the manufacturing company Materialise. The configuration of the pieces illustrated complex geometries that could not be produced in a single run using any other production process.

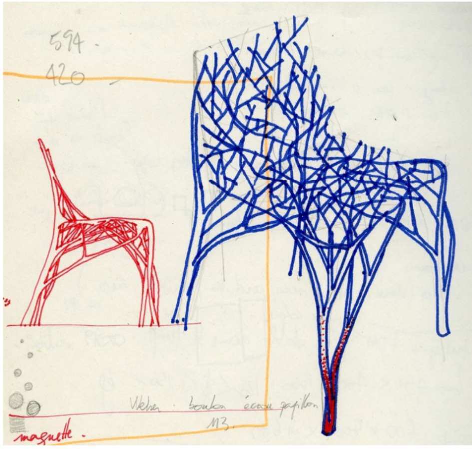

Figure 20. a) Solid C2 chair; b) Concept design (Source: a) Williams, 2006, p. 113; b) Jouin, 2014b).

Name	Solid C2 chair
Designer	Patrick Jouin (1967-)
Manufacturer	.MGX by Materialise (2004)
Materials	Epoxy resin. Stereolithography (SLA)
Size (mm)	height 772, width 394, depth 540. Seat height 450.

Rapid prototyping creates several changes in the product design process. As Williams (2006, p. 112) indicates, it blurs the conceptual difference between custom design and industrial design. There is the possibility of producing one-off designs with an industrial CNC machine.

Rapid prototyping produces every geometrical possibility, thus decoupling shape realisation from material or production constraints to a certain extent. The production constraints become the size limitation of the machine, production time, and the associated costs. However, it enables the design process to be confined to digital experimentation and to include other variables. Jouin's One_Shot.MGX stool, produced in 2006, is a foldable stool whose hinges are hidden in the structure, illustrating the possibility of new discoveries via production technique (Figure 21).

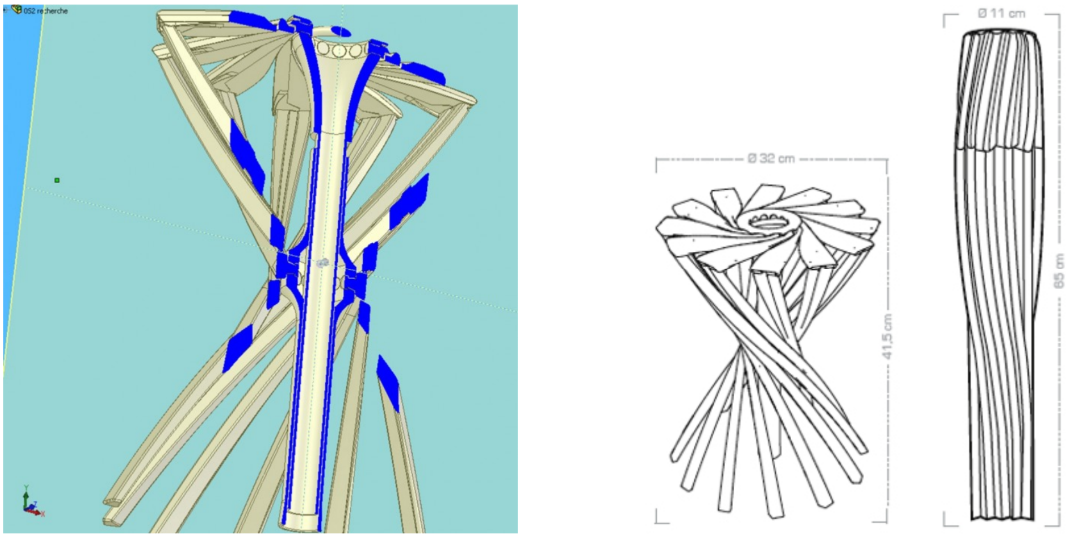

Figure 21. One_Shot.MGX: a) Section showing internal structure; b) Dimensions (Source: Jouin, 2014a).

Name	One_Shot.MGX
Designer	Patrick Jouin (1967-)
Manufacturer	.MGX by Materialise (2006)
Materials	Polyamide. Selective Laser Sintering (SLS)
Size (mm)	height 415, diameter 320 [open]; height 650, diameter 110 [folded]

2.3.3. Production Systems for Mass Customisation

From these two sets of experiments with injection moulding and rapid prototyping, it is possible to map out how technology encompasses several approaches to chair design.

Injection moulding is a production process that is only suitable for mass production. The cost of tooling implies a long investment return period. Rapid prototyping, on the other hand, is a production process for customisation. The classification of production systems (Section 1.2.2) comprises additive, forming, and subtractive systems. Considering them on a continuum of industrial activity whose opposite poles are mass production and mass customisation, forming production systems are enablers of mass production, and additive and subtractive systems permit mass customisation. Additive production systems enable a greater degree of customisation than subtractive ones. Nevertheless, between both ends of the spectrum there is the theoretical premise that is possible to develop forming production systems with a degree of flexibility to enable mass customisation.

As stated in previous sections, flexible manufacturing systems enable mass customisation. Subtractive production systems, such as milling machines, laser-cutters or water-jet cutting machines have been widely used to implement mass customisation. The use of this type of production technology has determined the development of specific design methods derived from construction principles, which then lead to the creation of distinct formal possibilities. Lisa Iwamoto (2009) categorised digital fabrication techniques as sectioning, tessellating, folding, contouring and forming.

Figure 22. a) Antler chair; b) Nesting (Source: Diatom, 2011).

Name	Antler chair (from SketchChair)
Designer	Diatom Studio
Manufacturer	(open source)
Development	2009-2010
Materials	Plywood
Size (mm)	(customisable)

Sectioning is a technique that requires dividing a three-dimensional geometry into two-dimensional sections. After production, the two-dimensional sections are assembled in interlocking fashion to achieve the final three-dimensional geometry. The production process consists of the use of two-dimensional digital files to guide the cutting machine. CNC routing, laser-cutting or water-jet cutting enable production from two-dimensional digital files. The SketchChair example featured in Section 2.1.5.3 employs this technique as part of the design system developed to generate and produce the designs (Figure 22).

Tessellating is the decomposition of a three-dimensional surface into a collection of discrete components which function like building blocks. Each block can be two- or three-dimensional. This technique can accommodate different types of resolution, depending on the size of the subdivision of the surfaces. The possibility of using different subdivision algorithms can generate a variety of designs (Figure 23). Depending on the number of dimensions of the shape, CNC milling can also be employed in addition to the production processes used in sectioning.

Figure 23. a) R18 Ultra Chair; b) Three-dimensional model (Source: Weisshaar et al., 2014).

Name	R 18 Ultra Chair
Designers	Clemens Weisshaar (1977-) Reed Kram (1971-)
Manufacturer	Audi Lightweight Design Center, Germany (2012)
Development	2011-2012
Materials	Carbon composite with micro sandwich and carbon rubber composite (shell), aluminium (legs)

Figure 24. a) Pressed chair; b) Sheet metal stamped part (Source: Moormann, 2014; Thaler, 2014).

Name	Pressed chair
Designer	Harry Thaler
Manufacturer	Nils Holger Moormann, Germany (2011)
Development	2010-2011
Materials	Stamped aluminium
Size (mm)	height 800, width 510, depth 525. Seat height 470.

Figure 25. a) Brazil chair; b) Milled block (Source: Warmann, 2010; Wildrig, 2009).

Name	Brazil chair
Designer	Daniel Widrig
Manufacturer	Monolito, Italy (prototype)
Development	2009
Materials	Laminated wood sheets (milled on a 5-axis CNC router)
Size (mm)	height 900, width 650, depth 700

Folding requires unwrapping a three-dimensional surface to a two-dimensional surface. It is a common technique in sheet metal design and can be employed for materials which can be bent without breaking. This production technique often requires auxiliary jigs to produce the final three-dimensional shape (Figure 24).

Contouring encompasses milling and turning. It is based on subtractive processes in which the final shape is machined from a single block. Unlike the other techniques described, the three-dimensional geometry is worked out in detail, which makes this technique the most precise of those listed above. The limitation on shapes is related to the number of axis of the machine or the type of CNC machine. However, the production processes involve greater wastage of material (Figure 25).

Forming is the last technique defined by Iwamoto, although it cannot be considered a technique like those mentioned above, but rather a class of production system. It employs digital fabrication as a medium to produce a mould that is used to generate the final shape. Digital assisted tools enable non-standard moulds to be produced, therefore making them suitable for mass customisation. The forming processes are not inherently digital and can be combined with other types of processes, whether analogical or digital. The advantage of digital fabrication for forming processes is the possibility of creating customised production techniques, a definition which meets the requirements of mass customisation, particularly the need for manufacturing systems capable of accommodating a certain degree of flexibility (Sections 2.1.2 and 2.1.3).

As a mass production process, forming is probably the process most widely used in industrial design (Thompson, 2007, p. 11). It is employed in the manufacture of several artefacts in different materials, such as plastic, metal, paper, leather, and wood. Given this premise, there are several research possibilities for adapting forming production systems to accommodate flexibility, to enable mass customisation. The requirements are the production of low-cost tooling and reconfiguration to suit a large set of custom shapes.

Iwamoto (2009, pp. 110-111) states that there is a need for additional research into forming processes as a means of contributing to the leverage between the economy of means employed in mould production and the quantity of objects produced. In short, there is a need to develop production systems thoroughly aligned with the design intention.

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2.4. Forming Production Systems

"Manufacturing is continually in a state of transition" (Thompson, 2007, p. 8).

As explored in the previous sections, CNC machinery enable the models suitable for mass customisation to be established, within which the designer can translate the geometry into an appropriate CAM strategy. In these models of the design process, the design intention considers the direct use of CNC machines as the manufacturing medium, thereby including production techniques and material considerations as design variables. These approaches are suitable for the additive and subtractive processes. Product components that must be produced by forming processes are not suitable for direct CNC custom production. The use of CNC must therefore be researched as a medium for producing custom tooling parts which will, in turn, assist workers in moulding custom components. Whereas the problem of direct CNC production requires research into cutting, joining and finishing functions, the problem of forming for mass customisation requires research into reconfigurable tooling.

In forming manufacturing processes, tooling refers to a mould or a die which is used to form the final product. During the forming process, the shape and properties of the material are transformed and the development of this class of production system therefore differs from product development activities which rely on an existing production system. It focuses both on the optimisation of product features and on material transformation achieved by a dedicated machine. These two interconnected variables – the forming process and materials – are researched within the fields of mechanical engineering, industrial engineering, and materials science. Research in both variables must be concurrent, since it involves the synchronic evolution of both.

This section introduces the generic problem of reconfigurable tooling in the production industry, focusing on mass customisation issues. It then reviews the state of the art in wood bending, which is directly related to the case study for this research.

2.4.1. Reconfigurable Tooling Systems

The complexity involved in developing a mass customisation production system derives from the number of dimensions in which customisation is permitted (Section 2.1.3.1). Three-dimensional shaping of custom products encompasses several levels of separation between the geometrical CAD component and the CAM produced component. Rapid prototyping is the most direct means of production, followed by CNC routing. Forming techniques are the most indirect, since production is accomplished by a dedicated machine developed according to the specifications of the geometrical and material features of the product.

Moulds and dies have been used extensively in mass production for manufacturing long runs of the same shape. Significant advancements in forming processes can involve years of experimentation before they are ready for industrial application, as can be seen in the pioneering work of Michael Thonet, who experimented from 1830 to 1859 to perfect the industrial process for the production of his chairs (Sections 4.1 and 4.2). Similarly, Taiichi Ohno took nearly two decades to reduce the time required to change dies in the car industry, thus enabling lean production to become established (Womack et al., 1990, p. 62).

Mass customisation requires shorter runs and the production of different shapes. These issues have been considered in several industries in recent years, in order to develop reconfigurable tooling systems. Some of the approaches developed for a specific material are then benchmarked to other materials with minor changes.

In metal forming, incremental forming has evolved from spinning-based techniques to the creation of three-dimensional shapes using a roller as the tool that gradually expands the metal surface into the final shape (Hagan & Jeswiet, 2003). In 2013 an incremental forming process was patented (Ford, 2013) which enables custom components to be produced. The manufacturing process is able to produce all the possible geometries enabled by stamping. It comprises two CNC three-axis machines working simultaneously on both sides of the lubricated sheet metal surface to define the chosen geometry. The current development enables prototypes for the car industry to be produced.

Koc and Thangaswamy (2011) reviewed the development of discrete element-based tooling systems by analysing two types of applications suitable for sheet metal and plastic moulding. Reconfigurable pin tooling systems (Walczyk & Hardt, 1998) consist of a matrix of pins that can stamp or mould a three-dimensional shape. In profiled edge lamination (PEL), the moulding shape is achieved by a series of assembled profiles in which each laminate displays a bevelled top part.

In forming production systems, concurrent research has been undertaken to change the material state to accommodate shape change. Some of the principles can be applied to form sheet metal and thermoform plastic, with specific changes. These developments can be summarised as a set of principles: the continuous tooling shape must be transformed into discrete elements; the positioning of each element must be controlled to allow for the definition of different shapes; the configuration of the discrete elements can be either separate of densely packed (Walczyk & Hardt, 1998), a condition that is related to the specific properties of the material and the shape of the component.

Separate discrete elements change their position during the forming process and are often employed in cases where there is plastic deformation of the material.

The position of densely packed discrete elements is configured before the beginning of the forming process. This type of system is applied in cases involving materials in a liquid state, although it can also be used in situations involving plastic deformation.

2.4.2. Wood Bending

Wood bending is a technique for transforming the shape of wood without subtracting it from a block. It has been applied in the construction of several shapes for artefacts since ancient times. Figure 26 presents a classification of the different wood bending methods adapted from Navi and Sandberg (2011, p. 288).

WOOD BENDING

SOLID WOOD
- Planar bending
- Bi-planar bending

LAMINATED WOOD
- Laminated structural elements
- Plywood
- Laminated bending
- Continuous lamination

OTHER METHODS
- Green wood bending
- Transverse densification
- Kerfing

Figure 26. Classification of wood bending methods (adapted from Navi & Sandberg, 2011, p. 288)

Solid wood bending, which is the focus of this research, comprises two sub-types of bending. Planar bending is a sub-type that encompasses bending on a single plane. In the case of Thonet chairs (Chapter 4), this sub-type of bending is used to shape the seat frame, legs[12] and leg brace. Bi-planar bending, compound bending or three-dimensional bending are terms that describe a more complex sub-type of bending that occurs on two planes. The complexity derives from the need to change the direction of the wood fibres during the procedures, a condition that leads to an increase in local stress, which may cause failure. In Thonet chairs, this sub-type of bending is used for the back-rear leg unit and the back insert (Section 4.2).

In solid wood bending, pre-processing the wood is an essential stage of the method. The conditions defined in this stage influence the moulding procedures and the post-processing settings. Plasticisation must take place to allow for the successful deformation of the wood. The methods can be divided into two types of treatment: thermo-hydro treatment and chemical treatment (Figure 27).

Thermo-hydro treatments have been in existence since ancient times and some have not evolved into suitable industrial applications. Direct heating, which involves heating wood with fire is one such example. This was a plasticising method used in the construction of shipping vessels and in coopers' work.

[12] In early Thonet chairs. More contemporary versions are produced by woodturning.

Boiling in water is a plasticising method that enables wood to absorb moisture in order to transform its properties. Peck (1957, p. 10) states that this method is equivalent to steaming at atmospheric conditions, and is only suitable for plasticising portions of wood. Thonet's first experiments consisted of boiling a solution of water and glue to moisturise wooden slats (Section 4.1).

The remaining plasticising methods are suitable for industrial applications and their features are therefore characterised in the following subsections, taking other variables in the overall process into account, namely moulding devices, procedures and permitted geometries.

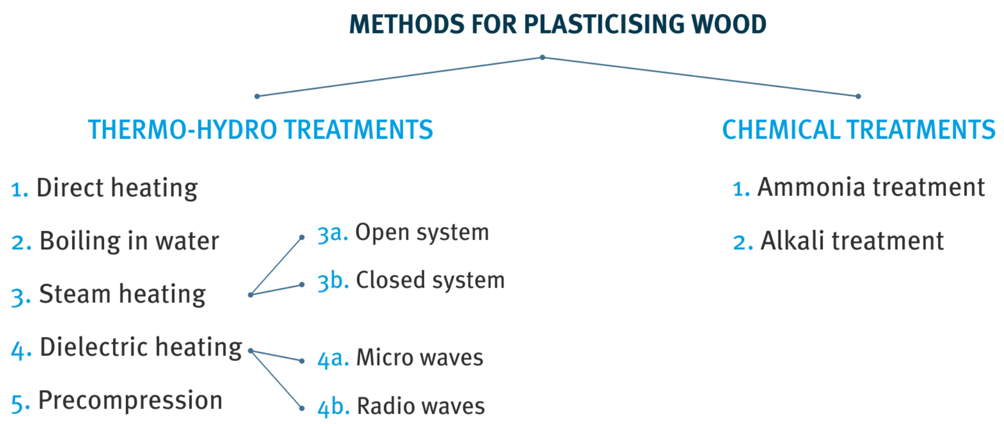

Figure 27. Classification of plasticising methods (adapted from Navi & Sandberg, 2011, p. 292)

2.4.2.1. Thermo-Hydro Treatments

2.4.2.1.1. The steam heating process

Steam heating is the method of plasticising wood with saturated steam at a temperature close to 100ºC (Peck, 1957, p. 10) to raise the moisture level to 20%-25%.

Peck states that dry stock with 12% or less moisture content needs to be soaked in water for days to obtain the conditions that enable it to be steamed. Since moisture absorption is greater at the ends, these zones must be isolated. In these circumstances, the steaming period is about 1.5 minutes for each millimetre of thickness and the drying period takes an average of 3 minutes for each millimetre.

a. Preparation

Wood selection is the first variable in successful bending. According to Peck (1957, p. 4), bending quality varies not only among different species but within the same species. However, tests to find a correlation between location, growing conditions, and bending properties have not proved conclusive.

Whereas bending possibilities relate to the species, the clearness of wood also plays a major influence. Given that a bent rod is subjected to compressive forces on the inner side and tension forces on the outside, the use of straight-grained wood is preferable for bending. Defects such as shakes, surface checks, decay, cross grain and the wood from the central core must be avoided (Peck, 1957, p. 5). Small knots are acceptable on the outer side but on the inner side they reduce the strength of the wood, leading to failure (Navi & Sandberg, 2011, p. 303). When dealing with small radii, clearness is mandatory.

Table 2 presents the minimum values for the radius in bending tests on a 25 mm thick board. 'Unsupported' means that wood is bent without any auxiliary apparatus, whilst 'supported' refers to the use of a set of auxiliary apparatus that allows for a smaller bent radius. Since the wood deformation is greater, it is necessary to use tensile steel straps and end stops which are clamped to the wood to prevent fracturing. These auxiliary devices work as a set and are therefore often termed 'strap-and-stop'. A metal strap is placed against the convex side of the wooden piece in order to absorb the tensile stress produced by the bending (Peck, 1957, p. 13), while slightly reducing the compressive stress on the concave side. End-stops are wooden blocks or clamps that prevent the wood from elongating more than 1%-2% (Navi & Sandberg, 2011, p. 297). It was Michael Thonet who observed this condition in the bending of smaller radii and developed this type of apparatus in the 19th century (Kollmann & Côté, Jr., 1968, p. 547).

SPECIES	LATIN NAME	SMALLEST RADIUS (mm)	
		supported	unsupported
Ash (American)	*Fraxinus sp.*	110	330
Ash (European)	*Fraxinus excelsior*	64	300
Beech (Danish)	*Fagus sylvatica*	43	370
Elm (Dutch)	*Ulmus hollandica*	13	240
Elm (Irish)	*Ulmus glabra*	43	320
Oak (American white oak)	*Quercus spp.*	13	330
Oak (European)	*Quercus robur*	51	330
Walnut (European)	*Juglans regia*	25	280

Bending of a 25 mm thick board with and without support by a strap-and-stop.
The bending procedures employ plasticised wood steamed at atmospheric pressure.

Table 2. Smallest bending radius in different species of wood
(adapted from Navi & Sandberg, 2011, p. 301)

Seasoning and storage also influence the behaviour of wood. Peck (1957, p. 6) reported experiments in which the bending of chair components and their geometries were correlated with the specific parameters of air-drying green wood to a predefined moisture level, storage under controlled temperature, and the moisture conditions before bending procedures.

Regarding the moisture level, Navi and Sandberg (2011, p. 304) observed that using air-dried wood below a particular moisture level may lead to surface checks which may result in compression failures. Moreover, steaming dried wood may cause distortion of the pieces and requires additional force to bend. The authors stated that compound bending is impractical in wood with a moisture level below 20%.

The finishing quality of the wooden piece is another variable which creates repercussions during bending. Given this consideration, smooth-finished materials are less likely to create splitting.

To summarise, the preparation of wood must obey the following conditions: it must be straight-grained and smooth-finished, and green wood is preferable to dried wood.

b. Retorts

In the steaming operation, wood plasticisation is accomplished with the use of retorts. Retorts are chambers that must be set at a temperature ranging from 70ºC to 120ºC to provide the necessary conditions for moistening the wood. The design of the retort must allow for saturation of the chamber and accumulation of some water at the bottom to create the necessary humidity conditions (Peck, 1957, p. 10). The required period for steaming varies according to several parameters, namely wood species, moisture content, wood thickness and desired curvature.

The need for a direct correlation between plasticisation procedures and the bending operations was observed by Peck (1957, p. 11) as follows:

"For efficient operation, the capacities of the retorts and machines should be SO balanced that the time required to load, steam and unload the stock from the retorts is correlated with the time required to load, bend, and unload it from the bending machines. Under such conditions, the steamed stock can be placed in the machine and bent with minimum delay."[13]

c. Moulding devices and procedures

Several methods and machines are employed in the process of wood bending, ranging from the traditional to the industrial. From the outset, the development of moulding devices must consider various different requirements: it must accommodate the set of specifications relating to the shape of the component to be produced and also the bending procedures and their time intervals.

In terms of industrial applications and the production of chair components in particular, there have been developments in the automation of planar bending procedures. The machines can be categorised by the type of geometric shape they are able to produce. Accordingly, there have been developments in hydraulic hot-plate presses which produce gentle curves, in open bending that supports the bending of arched shapes, and in revolving tables that enable the production of closed shapes.

[13] SO, written in capitals, follows Peck's texts.

With regard to Thonet chair components, the front legs are produced by hydraulic hot-plate presses (Navi & Sandberg, 2011, p. 307), which consists of submitting male-female moulds to hydraulic pressure. A single bending operation can produce several pieces. The same authors indicate the bending of 10 legs per cycle and the possibility of producing 150-200 legs per hour. Shape conformance and initial drying takes place within the moulds (Peck, 1957, p. 16). The drying time to 7% stabilised moisture level takes about forty-eight hours.

Open bending is a type of planar bending that generates arched shapes (Thompson, 2007, p. 199). Industrial machinery has been developed for automatic open bending (Figure 28), comprising machines with a mould positioned in the centre. The wooden piece is loaded into the machine with the strap-and-stop apparatus. Hydraulic pistons push the wood against the mould to achieve shape conformance in two cycles, as shown in Figure 28. When the automatic cycle is complete, an additional locking device has to be attached to maintain the piece in the bent shape. The moulded piece is then put in a drying chamber. This type of machine enables 50 to 100 pieces to be produced per hour.

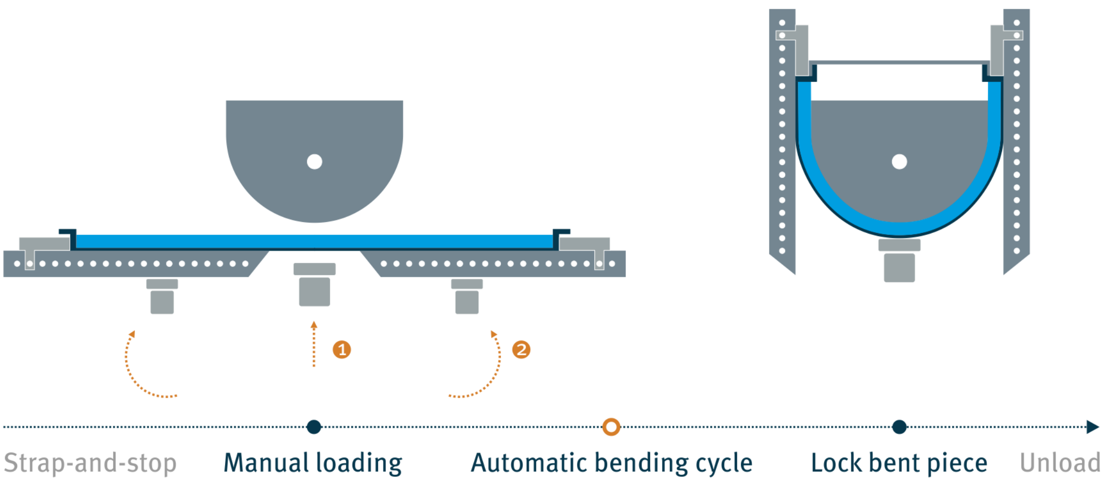

Figure 28. Open bending machine (adapted from Navi & Sandberg, 2011, p.308; Thompson, 2007, p.199)

Revolving tables are employed in the automatic production of round and trapezoidal closed shapes, such as seat frames (Figure 29). This type of machine comprises a mould mounted on a revolving device, a feeding mechanism, and a pressure roll. The procedure consists of clamping the wooden piece in the machine with strap-and-stop apparatus. During the cycle, the wood is fed into the mould and is compressed against it by the pressure roll to ensure shape conformance. According to Navi and Sandberg (2011, p. 309), this type of machine can produce 15-25 items per hour.

In compound bending, the procedures are still carried out manually by highly skilled workers (Navi & Sandberg, 2011, p. 310). The authors refer to the difference in training time for operators for single bending and compound bending to justify the complexity of the procedures. Training time for single plane bending takes a few months, whereas it may last two to three years for compound bending.

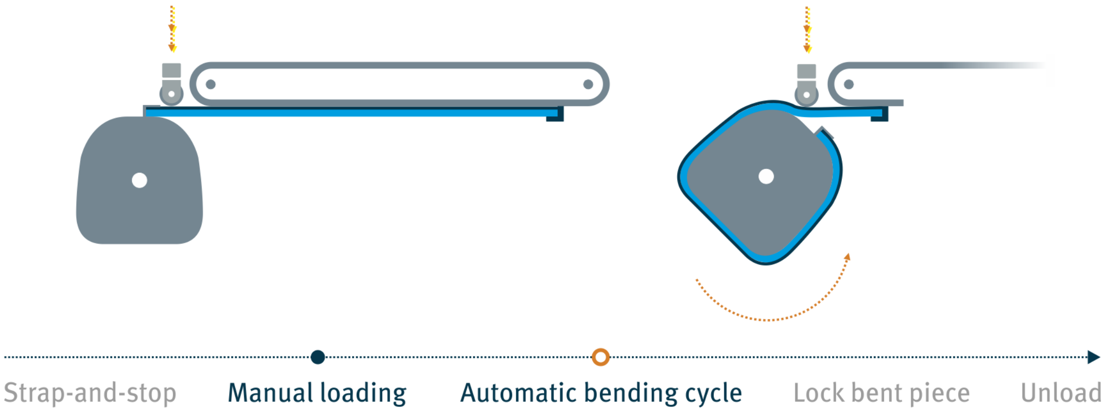

Figure 29. Revolving table bending machine (adapted from Navi & Sandberg, 2011, p.308; Thompson, 2007, p.199)

"In bi-planar bending, it is more difficult to theoretically determine the smallest bending radius. Not only the thickness of the material but several interacting factors are also of decisive importance, such as the profile of the turned wood piece, the torque, the length of the torque, the length of the work piece, the distance between the transitions to different planes etc" (Navi & Sandberg, 2011, p. 310).

2.4.2.1.2. Dielectric heating

Dielectric heating is as method which uses electromagnetic radiation to heat wood during plasticisation and drying. This type of plasticisation method has been researched since the 1970s, presenting problems in terms of the uniform heating of wood which have only been resolved in recent years (Navi & Sandberg, 2011, p. 313). The most commonly used technologies are radio wave and microwave heating.

The authors have presented the results of ongoing research focusing on the development of a production system for industrial application which integrates the pre-processing, forming and post-processing of wood. The bending operation is performed by a male-female mould that presses wood by hydraulic force. The mould is equipped with a built-in generator of radio waves to plasticise the wood.

The wood piece is set in place with strap-and-stop apparatus. The end-stops contain holes to permit the cooling of the wood during post-processing. 25% moistened solid beech wood is heated, bent and dried in the mould until it reaches 6%. The total cycle takes 26 minutes. In the presented development stage, the production system proved successful in producing gentle curves, such as those which can be observed in the front legs of Thonet chairs.

2.4.2.1.3. Pre-compression

Pre-compressed wood involves compression of the wooden fibres after the plasticisation. This method has been researched since 1910 but was only developed commercially in the 1990s (Navi & Sandberg, 2011, p. 320). The wood is compressed to about 20% in a longitudinal direction then is dried down to 12% moisture, enabling the wood to be bent in a cold state. The permitted radii are not comparable with the smaller examples obtained by the steam bending method. However, it is possible to bend a 25 mm beech rod into a 230 mm radius. Additional experimentation has successfully enabled cold-state bending of 100 mm rods.

2.4.2.2. Chemical Treatment

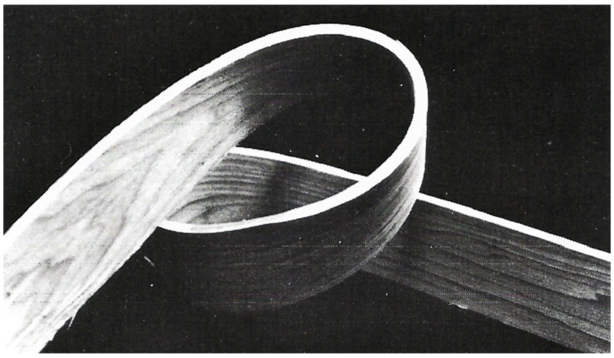

Figure 30. Wood bent with ammonia (Source: Keenan, 1985, p. 15)

The wood plasticisation can also be achieved with the use of chemical agents. Experiments have been carried out with several compounds (Peck, 1957, p. 11), although ammonia derived compounds have produced better results. Schuerch (1966) demonstrated that wood could be immersed in liquid anhydrous ammonia or subjected to anhydrous gaseous ammonia to acquire plastic properties. The author reported better results with the use of liquid ammonia than with aqueous or gaseous ammonia.

Davidson and Schuerch (1972) presented advances in the processing of this type of application, reducing the amount of staining left in the wood which occurred during the chemical treatment.

According to Schuerch, wood treated with liquid ammonia can accommodate complex shapes, whilst employing less force than steam plasticisation. When the ammonia has evaporated, the wood maintains its original wood characteristics.

Keenan (1985) reports experiments with liquid ammonia, concluding that the bending procedure results in reduced breakage and requires less apparatus. The author affirmed that wood can be fixed with clamps or tape during the 15-minute evaporation (Figure 30). The method requires specific safety conditions, since ammonia is a poisonous chemical.

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2.5. Hypothesis

Given the research questions and goals (Sections 1.3 and 1.4), the existing theoretical models for mass customisation (Section 2.1), digital design (Section 2.2), furniture design (Section 2.3), and existing forming production systems (Section 2.4), there is an opportunity for establishing an integrated model that improves the patterns of collaboration between the fields of design and engineering during the realisation of the design process and in the definition of the production process. Promoting closer links between these disciplines and processes may lead to the inclusion of the user in the design process in the future.

These premises lead to the formulation of the following hypothesis:

A generative design methodology comprising shape grammars and digital design tools enables a design language to be defined, transformed to expand the universe of possible solutions, and information to be generated for the production of custom designs.

2.6. A Model for Mass Customisation in the Furniture Design Industry

The verification of the hypothesis will be guided by the principles of active research, through the development and analysis of a single-case study. The selection of this type and mode of research follows the goals of circumscribing a finite set of variables for the complex phenomena that are related to the different areas of knowledge in which the research is set.

As described in previous sections of this chapter, mass customisation may comprise several models, developed according to the company and user context, previous models, and other related conditions. The use of digital design tools and generative design methods also involves several theoretical models and associated practices. Defining a single case study therefore establishes boundaries for the study of a finite set of variables. In the field of product design, furniture design is the area which contributes most towards defining the domestic environment, where people spend a significant part of their lives. The selection of this area of product design means that the research results can be applied to the design of other items of furniture.

The chair is the typology selected as a case study to frame the research. This choice allows for the direct study of a finite set of variables which are directly related to both the design process and the human body. Therefore, although the study focuses on the development of design methods, the choice of the chair enables the results of the research to be related to other subjects, such as aesthetics, ergonomics, construction principles and structural resistance.

The theoretical model is the conceptual structure which guides the active research and organises the different areas of knowledge involved in the research.

2.6.1. Theoretical Model

The theoretical model combines an interpretation of the existing principles in the literature and the specific goals of this research.

Jochen Gros (2001) researched furniture design methods for mass customisation, in particular through the use of CAD with direct links to CNC production (Section 2.1.3). The research focused on the optimisation of three-axis CNC cutting and engraving to define the constraints framing the design process. The author recommended the creation of new vocabularies of shapes encompassing customisation as future research in the field. This issue is directly related to the generation of versions.

The generation of versions, i.e. alternative design solutions defined by a designer, is an issue addressed in shape grammars literature. The use of shape grammars in furniture design was pioneered by Terry Knight (1980). The Hepplewhite-style chair-back shape grammar uses this formalism to encode a design style and generate custom chairs within a predefined language (Section 2.2.2.4). The same author (1981) showed how stylistic evolution can be explained as the transformation of the underlying grammars, thereby providing the means to develop an encoded design language into novel iterations (Section 2.2.2.3).

These issues are accommodated in the theoretical model for mass customisation defined by José Duarte (2001). The model was defined for architectural design, but can equally be applied to product design. It proposes the establishment of a design system and a production system controlled by a computational system that supports both the exploration of solutions and the generation of data for CNC production. The design system permits a design language to be defined through the use of shape grammars (Section 2.2.2.3). Rule application involves additional computational methods, namely simulation and optimisation to evaluate the generated solution. The design process is encoded in CAD to allow for the interactive exploration of designs. Although not implemented on a constructional level, the link to a production system was outlined as the condition that would enable mass customisation.

This research comprises the first application of Duarte's theoretical model in the product design field and, more specifically, in the furniture design industry. The following subsections detail the adaption of the model, taking the specific conditions of the case study into consideration.

2.6.2. Case Study

The case study was defined according to the following requirements:

1. Verification of the theoretical model in a representative furniture design typology;
2. Selection of an existing design style, representative of mass production.

With regard to the first requirement, furniture design is employed in this research as the product design field of application. Furniture design research takes into account the important role it plays in defining the domestic environment, as stated in the introductory chapter. The chair is selected as the experimentation typology for modelling a furniture design problem, as it requires direct input from the human body and allows for investigation of aesthetics and structural requirements (Section 2.3). These variables are present in other furniture and product design problems, which means that the conclusions from this study may be applied to similar problems in other furniture design typologies in particular, and other product design typologies in general.

In addition, the chair provides well-defined boundaries for the research. It enables the set of associated variables to be identified and the way in which their values may affect design results to be studied, thus leading to the envisaged mass customisation model. This condition also is related to the second requirement.

Thonet bentwood chairs were selected as the specific case study. Thonet chairs are symbolic of the mass production paradigm, since their technological and typological development has established mass production as the standard approach in the furniture industry since the 19th century (Chapter 4). Moreover, they can be analysed as customised standardisation since their components are modularised. Consequently, the original formulation of Thonet chairs permitted a degree of customisation for consumers, who could select from a list of predefined components, available in the company's catalogues. This condition provides a solid base to assess the evolution from customised standardisation into tailored customisation, the main purpose of the present research. In tailored customisation, consumers have access to a higher degree of customisation by tailoring a generic layout defined by the company. Given the specific goals of the research, Thonet chairs offer the possibility of studying whether an existing design style can be encoded to devise a generative design system to develop custom designs.

Regarding the study of the automated production system, Thonet chairs constitute a significant challenge. The wood bending process is highly manual, involves significant material constraints and still uses specifications and apparatus developed by Thonet in the 19th century. It is therefore not suitable for automatic production using the existing production systems. These conditions consolidate the boundaries of the research and limit the approach to the study of the production system, namely the conceptualisation of the principles for an automated production system. Furthermore, this type of investigation falls into the category of reconfigurable tooling systems for wood forming, which has been subjected to very little research.

The principle of researching an existing design style enables the results to be compared and validated against tacit knowledge, thus providing methods that can be adapted to model design problems with similar variables.

The theoretical model is adapted to the case study conditions, as shown in the model presented in Figure 31. The model aims to encode both the embodiment design phase of the design process into a generative design system, and the detail design and production phases, which establish manufacturing and assembly operations, into a production system. The goal is to assist the designer in the generation, exploration, evaluation and production of custom solutions that belong to a design language.

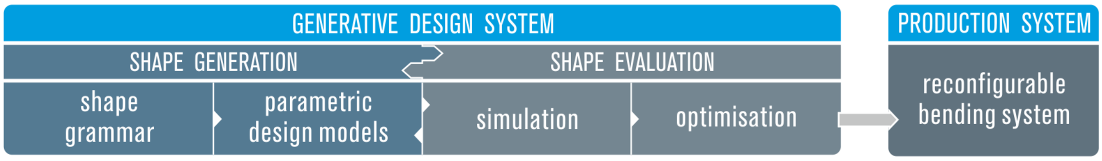


Figure 31. Design model for mass customisation in the furniture design industry

The generative design system (Chapter 5) comprises the interconnected subsystems of shape generation and shape evaluation, each comprising two parts.

The shape generation subsystem encompasses a shape grammar and parametric design models. The shape grammar is the formalism employed to encode the Thonet chair design style. The goal is twofold: 1) to explain the style as a design language; and 2) to enable new designs to be generated according to the established principles of the language. The second part of the shape generation subsystem comprises parametric design models, used to encode the shape grammar in a CAD software. The goal of parametric design models is to assist the designer in the creation of customised variants from each shape grammar topological version. In addition, parametric design models create a link to the subsequent steps of the design process, facilitating a certain kind of collaboration between design, focusing on the shape generation subsystem, and engineering, focusing on the shape evaluation subsystem.

The shape evaluation subsystem is established in the ongoing digital process from design to manufacturing. It follows the shape generation subsystem by introducing the engineering-related variables into the generative design system. The computer is used to ensure that a custom design fits the performance requirements. FEM is employed as the simulation technique for analysing each customised variant against the requirements of the ISO standards for domestic chair performance. In the event of failure, optimisation is used to search for a feasible configuration in a large solution space, thus meeting the predefined goal. This part of the system encodes aesthetics and material-related issues, formalised in the previous parts of the generative design system.

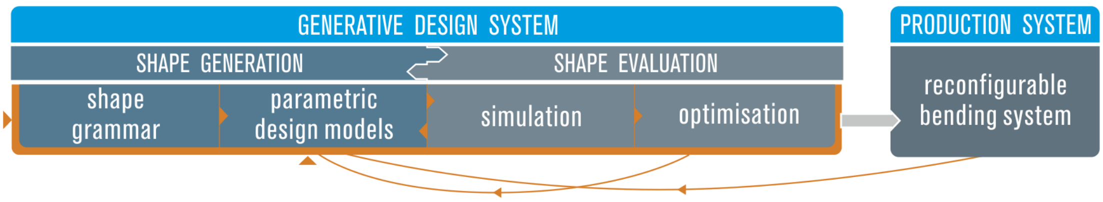


Figure 32. Transformation of the generative design system

The transformation of the design language (Chapter 6) readdresses the development of the generative design system (Figure 32). This principle can be summarised as both iterative and incremental. Iteration is a revision cycle of the procedures implemented, based on a reflective activity (Schön, 1983) to support refinement of the information encoded in the system.

Incremental transformation assesses the inclusion of additional information according to specific goals. In this thesis, incremental transformation is investigated as a means of opening up the solution space created by the shape grammar.

The third step in the verification of the hypothesis is the development of the production system (Chapter 7). The goal of the generative design system is the production of custom solutions through computer-assisted manufacturing. However, Thonet chairs are not optimised for the existing additive or subtractive production systems. As previously mentioned, this type of problem is categorised under reconfigurable tooling systems (Section 2.4). This condition establishes the approach to the conceptualisation of a reconfigurable tooling system for wood bending which is capable of producing custom Thonet chairs.

2.6.3. Theoretical Positioning

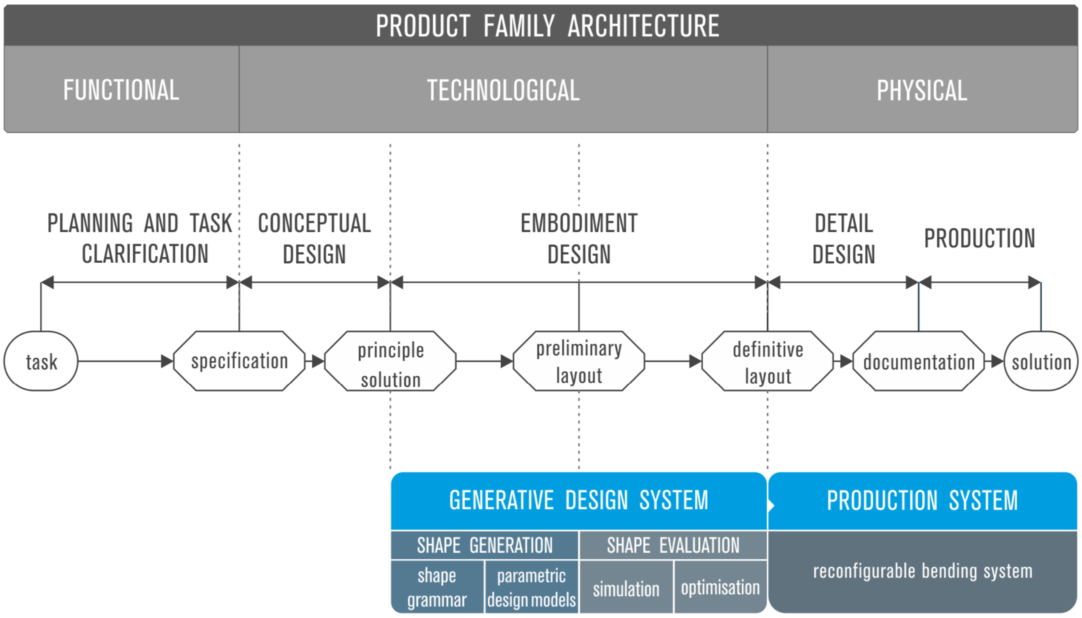
This research introduces a novel theoretical model for mass customisation in the furniture design industry. It can be summarised as an interdisciplinary approach to the product development process, and the scope of the process, which includes design and production definition. The novelty of the thesis (Section 1.5) can be further characterised by its positioning under the different theoretical backgrounds involved in its definition.

2.6.3.1. Positioning in Mass Customisation

According to the state of the art, the implementation of mass customisation in the furniture design industry (Section 2.1.3.6) comprises two primary strategies: customised standardisation and tailored customisation. Customised standardisation, which is based on modularity, is often implemented to improve pure standardisation strategies. Tailored customisation, which relies on modularity combined with digital design, is often implemented to improve pure customisation strategies. This thesis proposes a model to establish a tailored customisation strategy, by selecting a case study which embodies customised standardisation principles.

With regard to mass customisation implementation, particularly product family architecture methodology (Erens & Verhulst, 1997) which comprises three complementary models – functional, technological and physical – this research mainly addresses the issues involved in the technological model and tests their connection to the physical model.

Product family architecture can be analysed by mapping it to a conventional model of the design process (Figure 33). According to the adapted model of Pahl et al. (2007, p. 130) the design process is divided into five main phases. The planning and task clarification phase constitutes the functional model. The conceptual design and embodiment design phases correspond to the technological model. The definitive layout achieved by the technological model constitutes the input information for the detail design and production phases, which correspond to the physical model.

a)
b)
c)


a) Product family architecture (Erens & Verhulst, 1997)
b) Model of the design process, adapted from Pahl et al. (2007, p. 130)
c) Proposed model for mass customisation in the furniture design industry

Figure 33. Positioning of the proposed model for mass customisation in the furniture design industry (c) relative to: a) the product family architecture; and b) the model of the design process.

The functional model translates customers' needs into functional product requirements that serve as assessment criteria and will guide the development of the technological and physical models. The technological model is characterised by the definition of product attributes and functionality. During the development of this model, product features are designated in accordance with manufacturing capabilities and this information must include a strategy for creating multiple outputs from the product family architecture, which becomes the variation space for customisation. The generative design system proposed in this thesis encodes these issues for a furniture design problem. The transformation of the shape grammar addresses iteration in the development of the generative design system by expanding the initial solution space. The transformation serves the purpose of assessing the robustness of the proposed design process and the need for future use of the information encoded in an established product family architecture.

Information relating to manufacturing and assembly operations becomes formalised in the physical model. The connection between the generative design system and the conceptualisation of the production system proposed in this thesis systematises the translation of information between the technological and the physical model.

Product family architecture organises the backend operations of a company and end users customise products according to their own intentions by using an interconnected frontend application (Forza & Salvador, 2006, p. 74). Considering a dynamic mass customisation process consisting of the designer, manufacturer, and user, this research focuses on closing the gap between the first two, by focusing on the backend operations, whilst establishing an integrated model that allows for the active future participation of the end user in the furniture design process.

Frontend applications, such as configurators (Section 2.1.4.1) or user toolkits for innovation (Section 2.1.5.1), enable end users to interact with the company, to select a customised solution or even to create novel solutions. These frontend applications may comprise a different structure than the one used in the backend operations, in order to improve usability for the end user (Blecker et al., 2004, p.34). Therefore, there is the theoretical possibility of establishing the backend operations of a product family architecture and develop the frontend application separately. The model proposed in this thesis takes these premises into account and focuses only on the backend operations. Consequently, the frontend application, which is outside the scope of the thesis, must be developed according to the characteristics of the envisaged business model, the end users' needs, and the extent of customisation.

In his review of the application of artificial intelligence techniques to mass customisation, Simpson (2004) reported on the success of grammar-based approaches in product design. Given the functionality of the technological model, the use of shape grammars is a productive approach to automating product generation within a design language. According to the state of the art in mass customisation and product design, there are no connections between a technological model and a physical model defined by shape grammars. This condition can be further examined in the context of digital design.

2.6.3.2. Positioning in Digital Design

Considering the issues involved in the computer-aided design implementation of shape grammars (Beirão, 2012, pp. 45–47) and prior conceptualisation of the schema of relations that guides algorithmic composition and relationships in parametric design models (Aish, 2005), this thesis proposes a novel approach. It formalises a method for converting shape grammars into set grammars by excluding embedded results, thereby enabling them to be implemented as a set of different parametric design models. Each parametric design model allows alternative design solutions to be explored within a fixed topology defined by the shape grammar rules. This approach ensures the computerised implementation of shape grammars and the coupling of parametric design models to a generative design mechanism in order to guide the encoding procedure.

In addition to generating multiple variants, the other benefit from investing in parametric design models comes from their integration with performance-based tools, namely simulation and optimisation (Section 2.2.4). From a problem-solving perspective, computer-aided tools assist in the gradual progression from ill-defined to well-defined situations during the exploration of a design domain, and enable an optimal solution to be defined. Regarding Oxman's models for digital design, this thesis can be classified under the compound models envisaged using existing software (Oxman, 2006, p. 258–260). In this type of model, the designer interacts with the generation, representation, evaluation and optimisation modules in order to develop an integrated design process.

2.6.3.3. Positioning in Conventional Models of the Design Process

Cross (2000) distinguishes two main classes of design models: prescriptive and descriptive. Evbuomwan et al. (1996, p. 305) summarise them and characterise a third class, comprising computational models. According to the authors, the prescriptive models analyse the overall design process and propose systematic steps to achieve the goals; the descriptive models characterise the designer's activities during the realisation of the design process; and the computational models are concerned with the use of computational techniques to perform different activities throughout the design process.

This thesis proposes a prescriptive model involving the use of computational tools. Since the terms 'methodology', 'phase', 'step', and 'system' are often employed in the literature to characterise similar concepts, the scope of each term is defined here in terms of the approach adopted in this thesis. 'Methodology' is the process used to achieve a solution that solves an identified problem. Sets of steps that attain a sub-goal are defined by the term 'stage'. Sets of stages can be grouped as a 'phase'. Phases, stages and steps refer to the design process. 'Methods' refer to procedures for the act of designing (Cross, 2000, p. 46). When these procedures are accomplished using specific tools, they are termed 'techniques'.

Given that the goal of the proposed model is to encode the issues involved in the design process using computational techniques, the term 'system' is used here. This term presupposes the existence of a mechanism in which the constituent parts interact to achieve a certain goal (Simon, 1996 [1969], p. 128). In the proposed generative design system, each subsystem corresponds to a sub-function of the overall system. Furthermore, each part of a subsystem achieves a more specific goal.

The proposed generative design system and its subsystems of shape generation and shape evaluation aim to encode knowledge from the fields of design and engineering. Considering the model of the design process defined by Pahl et al. (2007, p. 130), the generative design system aims to encode the embodiment design phase (Figure 33).

The shape generation subsystem is built up from the activities used to develop a principle solution into a preliminary layout. The preliminary layout must comprise the definition of shapes and materials for the product. In order to accomplish this working step, the designer uses the formal synthesis method (Bonsiepe, 1992, p. 221) to create a concordant set of rules that determine the formal identity: a) between different elements of a design in the case of a unique product and b) between different designs in the creation of a product family. These steps are described in the synthesis stage in Archer's model (Cross, 2000, p. 36), in which design proposals are outlined. The relevance of selecting this step – the principle solution – in the embodiment design phase as the starting point for the proposed generative design system is that in conventional design models deductive reasoning leads to a unique solution, whereas the aim of this thesis is to encode this type of reasoning as a set of rules that define a design language.

The shape evaluation subsystem aims to emulate the activities carried out whilst developing a preliminary layout into a definitive layout in Pahl's model of the design process. It can be compared to the development stage in Archer's model. The activities must be accomplished through collaboration between design and engineering to validate the design proposal that constitutes the definitive layout. In order to achieve these goals, the shape evaluation subsystem in the proposed generative design system assists the designer in encoding the variables relating to the evaluation of the custom designs generated by the previous subsystem.

In a conventional design process, creativity is tapered throughout the steps and stages until it reaches the solution that is optimised for fabrication. In this thesis, the aim is to extend creativity to the latter steps of the design process, by incorporating knowledge of the underlying principles of design generation, the physical behaviour, and the fabrication restraints into the system itself. To summarise, the generative design system is a device that augments the designer's ability to define and explore the universe of preliminary layouts within a design language and supports the automatic search for definitive layouts.

The information created in the generative design system connects to the production system. The production system encodes the activities performed in the detail design and production phases, during which the manufacturing and assembly operations are established.

2.6.3.4. Positioning in the Development of Production Systems

This thesis follows the terminology of Groover (2010 [1996], p. 4) which considers that although "production has a broader meaning than manufacturing" both words "are often used interchangeably" in the context of products. The terms encompass the activities of fabrication and assembly. Like 'production' and 'manufacturing', the term 'system' is used as a broader meaning of the term 'process'. "Production systems consist of people, equipment, and procedures designed for the combination of materials and processes that constitute a firm's manufacturing operations (Groover, 2010, p. 16)." Likewise, 'forming' is broader than 'bending'.

The hypothesis underlying this research comprises the problem of producing customised designs with the use of digital design tools. However, the original formulation for wood bending production is not suitable for direct CNC production, and research into forming is therefore required. In this class of production system, research in reconfigurable tooling systems (Section

2.4) analyses the forming systems used in mass production. Existing processes, usually subtractive ones, are then used to develop dedicated tooling systems that allow for shorter runs of products.

This thesis considers the conceptual development of a reconfigurable tooling system for wood bending, on the basis of the requirements defined by a design language encoded in a generative design system. This is a novel approach in the state of the art in wood forming research in general, and wood bending in particular.

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2.7. Summary of the Chapter

This chapter reviewed the state of art in the constituent areas of the research: mass customisation (Section 2.1.), digital design (Section 2.2.), chair design (Section 2.3.), and forming production systems (Section 2.4.). The formulation of the hypothesis (Section 2.5.) and the theoretical model for its verification (Section 2.6.) conclude the chapter. Its organisation comprises a progressive arrangement of the subjects from a macro level to a micro level.

The mass customisation section (Section 2.1) started by introducing the post-industrial society (Section 2.1.1) that is the paradigm in which the research is set. This paradigm shift creates the founding conditions for the establishment of mass customisation as the industrial model which best embodies the principles and the dynamics of the post-industrial society.

The definition of mass customisation (Section 2.1.2) analysed and described the required changes in companies' organisations, which evolved from pyramidal structures into network organisations. The application of technology was analysed as the driver of change, both internally and externally. Regarding the main focus of companies, it was characterised the shift from production, the mass production postulate, to consumers, the mass customisation postulate. This premise was examined more precisely by analysing the five strategies that constitute the spectrum from mass production to mass customisation: pure standardisation, segmented standardisation, customised standardisation, tailored customisation and pure customisation. These strategies became the reference for additional analysis, categorisation, and comparison of several features throughout the chapter.

The implementation of mass customisation (Section 2.1.3) was characterised by detailing aspects of the production cycle – design, fabrication, assembly, and distribution – of the aforementioned strategies, with greater emphasis on characterising the design and fabrication processes, which are the subjects of the thesis. The subsection discussed the establishment of these processes, designated as the product development process, and their implementation in companies. Consequently, there was the presentation of modularity as the decisive factor regarding the implementation and of product family architecture as the integrative methodology for mass customisation. Furthermore, the implementation of mass customisation in the furniture design industry was detailed by presenting the C-Moebel case study. This case study was selected because it embodies common aspects with the ones proposed in the research. In particular, the focus on design discipline and its connection towards production and the use of digital design as a mean to complement and improve modularity.

Mass customisation requires a more active role for the consumer, who interacts with the company by means of configurators. Section 2.1.4. detailed this kind of mediated-interaction, by analysing configurators as frontend application devices that enable companies to communicate the result of their internal processes to consumers. The subsection discussed the premise that the result of an internal product development process can be communicated to consumers differently, thereby justifying the approach undertaken in the present thesis.

Section 2.1. ended with the discussion of the progressive blurriness between producers and consumers, by mapping multiple approaches. The approaches were characterised according to the promoter of the action, whether is a company, an individual or group of individuals, and the type of value created. The issues presented in this subsection do not relate directly with the scope of the research which is focused on the backend operations of a product development process. Rather, they offer insights for the future implementation of the proposed model in the industry, by discussing different possible approaches.

Mass customisation relies on modularity to implement customised standardisation strategies (Section 2.1.3). The transition to tailored customisation strategies relies on the use of both modularity and digital design. Therefore, Section 2.2. specified the existing digital design models and inquired their suitability in the product development process. Specific methodologies, methods, and techniques were characterised according to their application in contemporary design practice. This examination aimed to discuss a redefinition of the design activity itself and to support the decisions made in constituting the theoretical model proposed in this thesis. In particular, the approach undertaken in establishing and developing the generative design system and the production system.

After reviewing the state of the art regarding the macro (Section 2.1) and meso (Section 2.2.) levels of the research, Sections 2.3. and 2.4. discussed aspects concerning particular aspects of the case study of the thesis. Namely the chair (Section 2.3.), which is the selected typology and forming (Section 2.4.), which is the selected class of production systems.

In Section 2.3. the chair was presented as the selected typology for experimentation in the field of product design. The selection of the chair was justified by the embodiment of several features which are observable in other product typologies, thereby enabling the conclusions of the research to be generalised to other cases by inductive reasoning. Furthermore, technology-driven experiments were presented, thus contextualising the present research and its approach in the particular field of chair design. The subsection ended with a discussion relating production systems applied to chair design with previously presented subjects, namely mass customisation and digital design. As a consequence it was identified the gap within the state of the art that justifies the research in forming production systems, which is proposed in the thesis.

Accordingly, Section 2.4. presented forming production systems, particularising the steps in transforming them to meet mass customisation requirements. The subsection then detailed the aspects related with the wood bending technique, which is addressed in the case study, in order to clarify the constraints and possibilities afforded by the technique.

The chapter ended with the formulation of the hypothesis (Section 2.5) and the presentation of the proposed model for mass customisation in the furniture design industry (Section 2.6.). The subsections detailed the adaptation of proposed model to accommodate the specific goals of the research and the guiding principles of the case study. Then, the proposed model was positioned relative to the state of the art. Regarding mass customisation, it was clarified the envisaged tailored customisation strategy and the specific addressed models – technological and physical – in the product family architecture. The positioning in digital design justified the selection of the combined use of shape grammars with parametric design and performance-based models to constitute the generative design system and to establish means to connect the digital information to the production system. Afterwards, the proposed model was positioned relative to the conventional models of the design process, specifying the equivalencies between the steps in the design process with the parts of the proposed generative design system and the production system. In addition, the terminology regarding this topic was clarified. To conclude the subsection, the proposed model was positioned relative to the development of production systems, and the respective terminology was clarified.

This chapter overviewed the theoretical background of the research and contextualised each subject relating it to the present research.

3. Methodology

This chapter presents the research methodology followed in the development of this study. The general concepts of the methodological approach are introduced in accordance with the features of the research problem. The research structure is then overviewed and detailed according to the methods used in the three main phases: analysis, construction, and synthesis.

3.1. Research Strategies

3.1.1. Qualitative Methodology

This study is positioned within the framework of qualitative methodologies. The research approach was selected following analysis of the research goals (Section 1.4), the characteristics of the phenomena studied (Chapter 2), and the skills and motivations of the researcher.

According to Maxwell (1996, p. 17), qualitative methodologies should be employed when the purposes of the research focus on understanding the meaning of actions, contexts and events, identifying unanticipated phenomena and their influences, developing causal explanations through interpretation, and providing a better understanding of the process rather than the outcome.

3.1.2. Mode of Research

After defining the methodological positioning for the investigation, the research was structured. According to the design research taxonomy presented in the introduction (Section 1.1), this study is positioned between 'praxiology', the study of practices and processes, and 'phenomenology', the study of the form and configuration of artefacts.

Although there are different taxonomies and definitions for classifying similar modes of research in the design field, as summarised by Frankel and Racine (2010), this study was carried out using active research, according to Archer's definition (1995, p. 11). The hypothesis and associated sub-questions were verified using systematic procedures that construct a new model for mass customisation in the furniture design industry. These procedures are developed and verified through research involving a single-case study.

As defined by Yin (1994, p. 13), a case study is "an empirical inquiry that investigates a contemporary phenomenon within its real-life context, especially when the boundaries between phenomenon and context are not clearly evident."

This type of research method is suitable in cases where it is important to test and evaluate new models and there is no single right answer for the research topics (Yin, 1994, p. 15).

The case study was selected after examining the type of initial research questions, which were focused on the 'how' and 'why' of the actions and on the level of complexity of the phenomena. Defining a single-case study meets the following objectives: a) providing a framework for comparing mass customisation with mass production; b) allowing for comprehensive examination of the premises of the theoretical model through practice; and c) pursuing an explanatory objective beyond the particular conditions of the single case.

The definition of the single-case study is used as an instrumental way of studying a broader phenomenon. The use of this research method allows for a degree of tailoring for some variables whilst pursuing a holistic view of the process. Furthermore, it enables the different aspects to be examined and correlations to be discovered through a systematic interpretive process (Gummesson, 2000).

To summarise, two interlinking levels of knowledge are explored in the case study: the empirical, established by data collection and development, and the theoretical, determined by the inductive process of analysis and interpretation.

3.1.3. Analysis and Validation

The development of a single-case study through action research includes a dialectic action and reflection strategy in order to produce knowledge (Schön, 1983).

The process of inferring the conclusions is accomplished through analytical generalization (Yin, 1994, p. 30). The theoretical concepts described in the state of the art and in the theoretical model for verification (Section 2.6) provide the logical framework for analysing and interpreting the case study results.

There are three levels of analysis. The first comprises analysis of the overall structure of the case study in terms of the general goal of implementing mass customisation in the furniture industry. The second level addresses the establishment of the research phases and their interconnections. The third level assesses each methodological step against the particular field of knowledge and procedures developed to implement the study.

These principles are consistent with the internal and construct validation criteria used in qualitative research. Internal validity focuses on the logical relationship between the research topics, created by discussing them in order to eliminate ambiguity, thereby clarifying the conclusions of the study. According to Marczyk et al. (2005, p. 159), the goal is the construction of an argument that excludes other possible explanations of the results.

Construct validity enables the integration of the research variables and observed phenomena into a coherent theoretical model (Meyer, 2001, p. 345). In order to improve the construct validity, the study must follow two requirements. Firstly, its definition must comprise clearly-defined variables, thereby circumscribing the scope of the research. Secondly, it must be built upon a solid theoretical model to strengthen its foundations (Graziano and Raulin, 2004 cited in Marczyk et al., 2005, p. 190).

3.2. Research Methodology

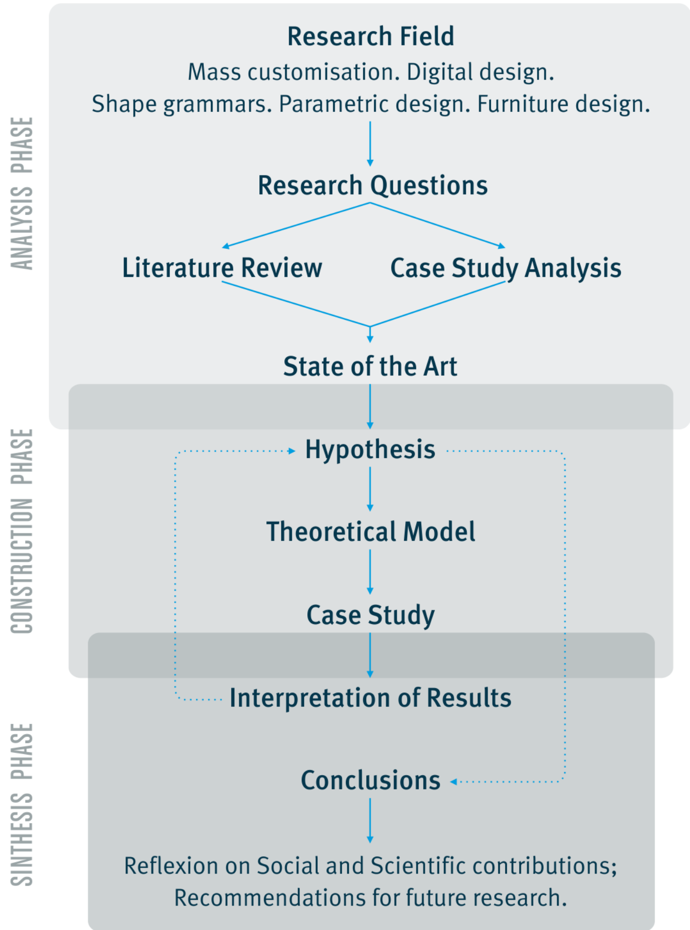

Figure 34. Research structure

The research methodology is structured according to the guiding principles identified in the previous section (Figure 34). The eleven systematic stages are categorised into three phases: analysis, construction, and synthesis.

3.2.1. Analysis Phase

The goal of the analysis phase is to define the research problem. This phase comprises the definition of the theoretical themes, formulation of the initial research questions, the literature review, and a comparison of the case study with other similar studies, in order to define the state of the art.

This research is set in the scientific field of product design, considering a theoretical definition that comprises: mass customisation, which determines the operational industrial model; design methods, which considers the models, tools and techniques employed in the design process; shape grammars and digital design, which designate the generative design methods and tools used in the development of the theoretical model and the process of verification; and furniture design which is the product design field in which the case study is set.

The analytical phase started by defining the initial research questions (Section 1.3) which guided the beginning of the study. The multidisciplinary scope of such questions determined that the initial literature review covered mass customisation, co-design, design methods, shape grammars, CAD-CAM tools, furniture design, ergonomics, production techniques, and research methods. In order to supplement the literature review, a set of case studies was selected for analysis. The goal was to provide knowledge of the correlation between theoretical concepts and practice-based applications. The selection encompassed the following types of cases: the design process used in the design and manufacture of objects on different scales; the use of CAD-CAM tools; generative design methods employing digital tools; the use of configurators to customise products; the description and generation of design languages by means of shape grammars.

The aforementioned methods included heuristic and hermeneutic activities in order to provide a reliable definition of the research problem and the formulation of the hypothesis. Given the constant evolution of the theoretical fields, the state of the art has been updated and refined throughout the research period.

3.2.2. Construction Phase

The construction phase is supported by deductive and critical reflection on the previous phase. This phase encompasses the formulation of the hypothesis, the development of the theoretical model for verification and active research focusing on the single-case study (Sections 2.5 and 2.6). Chapter 4 describes the previous information required to establish the case study and Chapters 5, 6 and 7 detail the procedures undertaken in this phase of the research methodology.

3.2.3. Synthesis Phase

The synthesis phase relies on the principles defined in Section 3.1.3. The interpretation of the results aims to provide a valid contribution to scientific knowledge in the fields in which the research is set. In particular, it aims to interpret the developed integrated model for mass customisation in the furniture industry, involving the use of a generative design system and a production system defined by shape grammars and digital design.

Based on the research findings and limitations, a set of recommendations are identified for future research in the areas of the research topic.

3.3. Summary of the Chapter

This chapter clarified the research methodology defined to conduct the present study. The research is structured around the principles of qualitative methodologies and focuses on the development of a single-case study through action research. Defining a single-case study provides the appropriate means for studying the phenomenon of mass customisation under a particular set of conditions determined by the theoretical model.

The definition of this methodology, including specific guidelines, allows for a degree of flexibility in developing the case study that reflects the scientific and academic rigour defining this research.

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4. Corpus

This chapter presents a brief history of Thonet bentwood chairs, considering the furniture context in which they were originally developed. It aims to provide a general understanding of the key features Thonet pioneered, with a particular focus on the design and production processes for the selected chairs that constitute the corpus used in this current research.

4.1. Thonet History

4.1.1. Initial Experiments

Michael Thonet (1796-1871) was born in Boppard-am-Rhein, Prussia (now Germany.) According to Wilk (1980a), Thonet established his own workshop in 1819, where he began to work in the traditional way.

It is not known whether Michael Thonet was familiar with other existing bentwood techniques at the time of his first experiments. There were examples of methods for bending wood with applications in the furniture, shipbuilding and wagon industries, namely the following, listed chronologically: three English patents granted between 1720 and 1794, intended for the shipbuilding industry (Navi & Sandberg, 2011, p. 36); the Windsor chair crest rail and continuous arm that had been made with a single bentwood element since the late 18th century; a laminated mahogany chair designed by Jean-Joseph Chapuis in around 1805 (V&A Images, 2014a); an entirely bentwood chair designed by Samuel Gragg between 1808 and 1815 in the United States of America; and an Austrian patent dating from 1821 for bending wheel rims from a single piece of wood (Alverà, 1987, p. 35). In the 1830s, Thonet began to experiment with producing furniture components with laminated veneers. The first experiment consisted of gluing several layers of thin veneers and bending them against a heated wooden form. Using this method he produced curved back rails for chairs (Wilk, 1980a, p. 7). The second experiment used slats measuring 25 x 4 mm, boiled in glue before the bending procedures. This method, which dates from the period 1836-1840, enabled him to construct his first chairs made entirely from bentwood (Figure 35). In comparison to the carved chairs made at the time, this type of chair required less labour and was lighter (Wilk, 1980a, p. 8). These chairs follow simplification principles observable in Biedermeier furniture, a style developed in the Austrian Empire and some German states (Oates, 1981, p. 165) following the period of economic impoverishment resulting from the war with Napoleon, from 1815 onwards. Rationalisation of the use of materials was reflected in fewer furniture types and simplified shapes.

The third experiment took place between 1840 and 1842 and focused on reducing the number of components. The chair designed in this period consisted of five components instead of the previous ten. This rationalisation was achieved by combining the side rails with the crest (top) rail into a single bentwood component. The backrest was strengthened with a back insert.

Figure 35. Boppard chair (Source: Minneapolis Institute of Arts, 2009; V&A Images, 2014b)

Name	Boppard chair
Designer	Michael Thonet (1796-1871)
Development	1836-1840
Materials	Laminated walnut frame with cane seat
Size (mm)	height 882, width 440, depth 465

After failed attempts to patent his wood bending method, Thonet exhibited his work at the Koblenz fair in 1841. During the fair, he caught the attention of Prince Metternich, who invited him to relocate to Vienna and offered assistance in the patenting procedures. In 1842 he patented the method in Austria, France and Belgium (Wilk, 1980a, p. 14).

Thonet continued to attempt to reduce the chair components, leading him to experiment with a compound bend. This particular sub-type of bending consists in bending in two directions and is achieved by twisting the wood during the bending procedure. Compound bending would enable him to combine the frontal plane curve of the backrest component with the lateral plane curve of the back legs, thus creating a single component. The procedure evolved from a two-step bending procedure to a unique bending operation, using laminated veneers.

The chairs for the Palais Liechtenstein (1843-1845) featured several characteristics which later became part of Thonet's design style. They were the first to employ compound curves and display rounded profiles. According to Dunnigan (1985, p. 56), this set of chairs combines three furniture styles. The Louis XIV style is observable in the curved legs and the inclusion of decorative motifs in the blending area between legs and seat. The Queen Anne style influenced the trapezoidal seat and curvilinear outline of the backrest. The Greek *klismos* chair, reflecting a major revival of the classical style since the 18th century as a result of archaeological discoveries, influenced the deflection of the rear legs. Thonet interpreted these styles with the lightness afforded by the bentwood method to create a unique style.

4.1.2. Production Experiments

Figure 36. Café Daum chair (Source: Wilk, 1980a, p. 19)

Name	Café Daum chair (No.4 in catalogues from 1859)
Designer	Michael Thonet
Development	1836-1840
Materials	Laminated veneer, solid bentwood
Size (mm)	height 900, width 420, depth 420

The conditions for refining the production process for mass production came with the first major contract, in 1849, for the design and production of chairs for the Café Daum in Vienna. The chair (Figure 36) which later became Chair No.4 in the catalogues displays different features that reduce the number of procedures required for its manufacture. The bent components are made from 8 mm mahogany veneers (Dunnigan, 1985), thus reducing the number of layers. The back-rear leg unit is made from four layers and the seat frame from five layers. It is the first chair to feature independent front legs. The lathe-turned capitals have both a decorative and a structural function, providing greater stability for the leg tenon inserted in the seat frame.

The wood bending method had evolved in comparison with the methods used for previous chairs, as Wilk (1980a, p. 19) claims:

"Instead of boiling all the laminates in glue and then bending them as a unit, the stacks of veneer were boiled in water, bent in the forms, and allowed to dry. After drying, the pieces were glued together, dried again, and then assembled."

According to Dunnigan (1985, p. 56), Thonet then received a similar commission for four hundred chairs for a hotel in Budapest.

The chair designed for the Palais Schwarzenberg in 1850, which later became Chair No.1 in the catalogues, reflects the progress made towards the goal of bending solid wood. The front legs are made from solid wood. The back-rear leg unit consists of a single bent rod. In the rear leg area, the rod has full thickness, but it is tapered in the top backrest area to facilitate the bending of the arched shape. Afterwards, the tapered area was reinforced with laminated veneers to achieve the required rigidity for the backrest.

Thonet displayed his work at the Great Exhibition of 1851 and was awarded a Medal for his chairs (Wilk, 1980a).

4.1.3. Large-Scale Batch Production

The Gebrüder Thonet[14] was founded in 1853. The company was organised as a large-scale batch production operation employing forty-two workers in addition to Thonet and his sons (Wilk, 1980a, p. 22): "nine cabinetmakers, one lathe turner, eight veneer cutters, two gluers, eight sanders, two stainers, ten finishers, and two assemblers."

The characteristics of the furniture, particularly the fact that it was lightweight and could be shipped disassembled, offered a major competitive advantage. The market at the time consisted of workshops and large cabinetmakers operating on a national basis. In addition, the furniture was heavier and its construction was labour intensive.

In 1856 he was granted a thirteen-year patent for bending solid wood using steam or boiling liquids. This gave the company the monopoly on this type of furniture in the Austrian Empire and other European countries until 1869.

The bending of solid wood was an innovation that permitted large-scale export. Nevertheless, Dunnigan (1985) refers to problems that occurred with the first shipments to the American continent due to moisture and heat affecting glue behaviour.

Process refinement is observable in the expansion of the company's operations. The year after the patent was granted, a factory[15] was established in the Moravia region (now the Czech Republic.) Workers in this factory received training in the sequential operations with time schedule considerations. This type of division of labour is similar to procedures introduced into the pottery industry by Josiah Wedgwood in the 18th century (Forty, 2005 [1986], p. 32–34), in particular the segmentation of the production process into more steps, fewer skilled workers receiving training, supervision, and the possibility of making multiples of the same design. According to Wilk, the workforce grew from seventy workers in 1855 to three hundred in 1860. Production increased from 10,000 items in 1857 to 50,000 in 1860. Five years later, with the opening of a new factory, the combined production was 150,000 items per year.

[14] Thonet Brothers

[15] This factory is currently the independent company TON.

4.1.4. The 1859 Catalogue

This growth and success can be explained by the combination of features mentioned above, together with marketing capabilities which can be summed up as two strategies: international catalogues and participation in international fairs. These pioneering approaches can still be observed in the contemporary furniture trade.

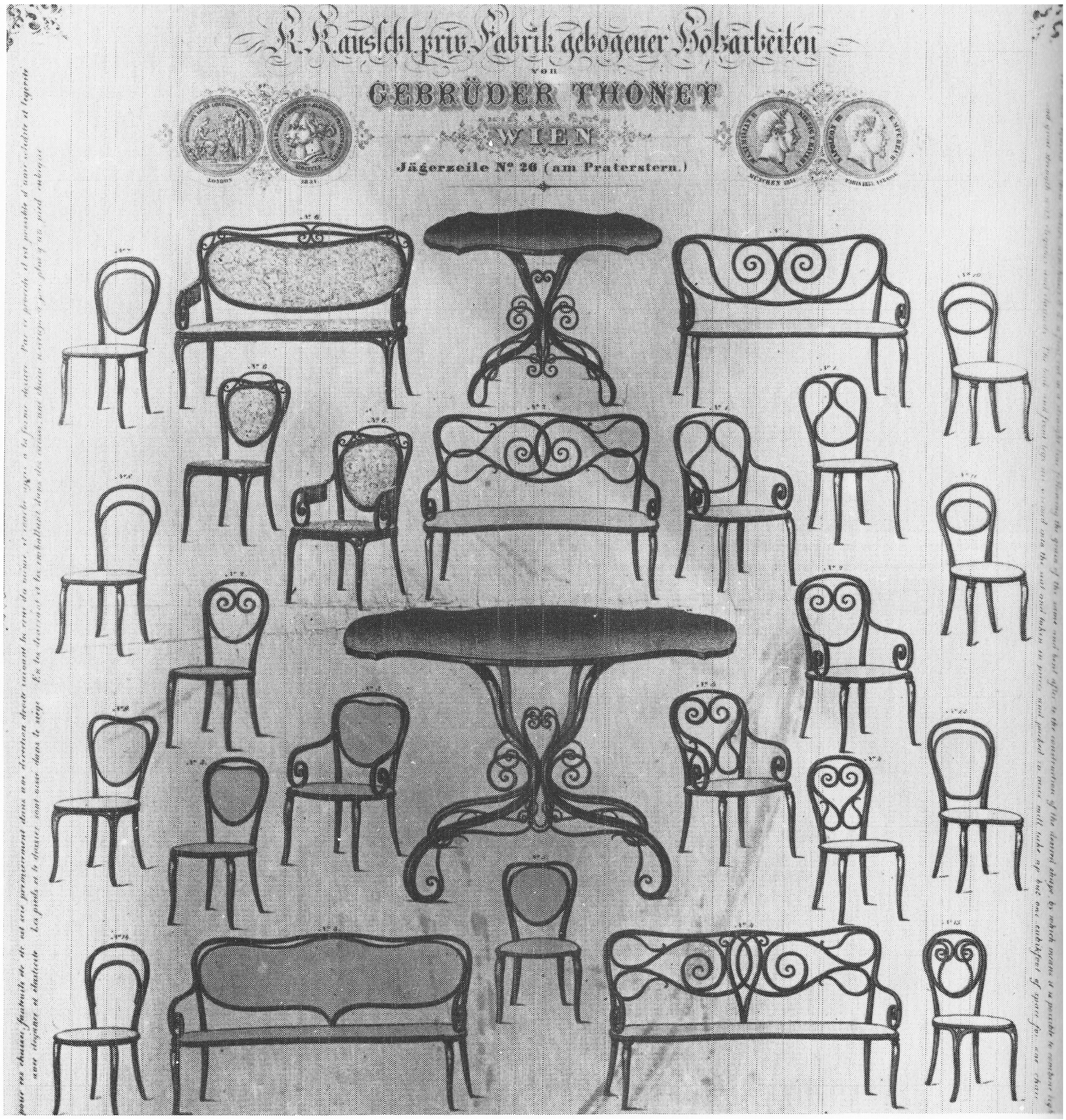

Figure 37. 1859 Catalogue (Source: Wilk, 1980a, p. 30)

In 1859 the company issued their first known catalogue (Figure 37) displaying twenty-six items of furniture: two tables, five canapés, five armchairs, and fourteen chairs. The catalogue was published in at least four languages: German, French, English and Italian. The text explained aspects of the wood bending method, the simple assembly procedures, finishes and the possibility of shipping thirty-six chairs per cubic meter. This information reflects the primary purpose of the chairs, which were meant to be used in public areas such as cafés, restaurants and hotels.

The catalogue illustrated items made from both solid bent wood and laminated veneers, following the design configurations of the early chairs. The five armchairs are variations on the chairs, featuring a wider seat, higher backrest and higher seat plane. The legs have capitals at the connection with the seat frame and are constructed in laminated veneer. Most of the designs are based on components which are interchangeable between versions, such as the back-rear leg unit, seat frame and legs, with the exception of the back insert.

4.1.5. Chair No.14

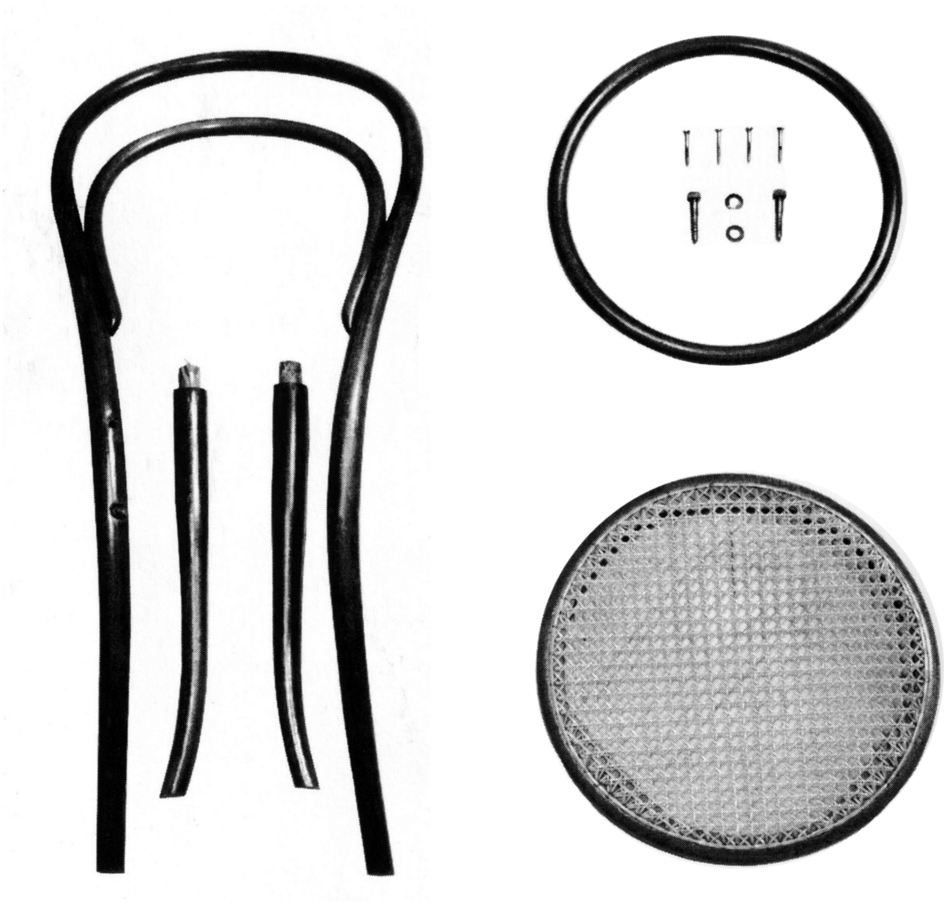

Figure 38. Chair No.14 disassembled (Source: Wilhide, 2010, p. 28)

Chair No.14 was the simplest chair and the least expensive item in the catalogue (Wilk, 1980a, p. 32). It had been refined for years until the design was optimised for the production methods (Alverà, 1987, p. 40–44). The 1866[16] version is composed of six bentwood components (Figure 38): the back-rear leg unit, back insert, two legs, seat frame and leg brace, which is a hooped

[16] Date of introduction of the leg brace, according to Wilk (1980a, p. 39).

stretcher rail. A lathe-turned capital was not used in the construction of the front legs, thus excluding decorative elements from the design. The seat frame was constructed from a bentwood piece with a scarf joint. Corner blocks strengthen the connection between the front legs and the seat frame, and the seat support was made of woven cane. The back insert was attached to the back-rear leg unit by four screws. This was the default construction assembled in the factory. The disassembled format was intended for shipping. The final configuration required the following operations: attaching the back-rear leg unit to the seat frame with two bolts, plugging the legs into the seat frame with glue, and attaching the leg brace to the four legs with four screws.

The success of Chair No.14 led to the construction of a new factory with dedicated production during the 1860s (Wilk, 1980a, p. 36). The optimised trade-off between design and production, and the production volume are the reasons why Chair No.14 is considered the first Modern chair.

4.1.6. Term of the Patent

According to Wilk (1980a, p. 33), during the 1860s and early 1870s, Gebrüder Thonet set up four new factories and opened up branch offices in several European cities, a development that reflected the success of bentwood furniture.

From 1868 onwards, one year before the patent expired, several companies started to build factories near Thonet's locations in order to copy the production methods, taking advantage of the specialist workforce and the proximity of certain forests, which were a source of raw material (Thonet Company, 1980a). From 1869 onwards, several other bentwood companies started to sell copies of Thonet's designs, some of which used the same numbering for items.

Increased competition led to the development of new designs. Chair No.18 features simplification principles similar to Chair No.14. It comprises the first back insert connected to the seat frame, thus providing better lumbar support for the user and greater stability for the chair.

4.2. The Thonet Design System

4.2.1. Production Methods

The wood bending method evolved out of more than two decades of continuous experimentation. Throughout the method, several woods were tested and Thonet concluded that beech wood had the best properties for solid wood bending. The evolution of techniques allowed for close correspondence between the design style and the manufacturing procedures. The method described by Wilk in 1980 has been confirmed by direct visits by Dunnigan to an American factory (1985, p. 60–61) and by Thompson to the German factory (2007, p. 201), which means most of the methods and the techniques developed in the 19th century are still used in the production of the chair components nowadays.

The following description comprises the steps from transformation of the logs to the final product[17]. The logs are cut into boards, which are air-dried until they reach 20%-25% moisture. Next, straight-grained and knot free wood is selected, cut into square profiles and lathe-turned into circular shaped profiles (Figure 39-1).

Figure 39. Steps in the bending of a back-rear leg unit (adapted from Thompson, 2007, p. 200)

The rods are soaked in water at 60ºC for 24 hours to raise the moisture level to 30%-40%. They are then put in retorts (Wilk, 1980a, p. 26), which are steam pressurized chambers (Figure 39-2). According to Thompson, the parameters are set to 104ºC for steam and 0.6 bars for pressure. The steaming time depends on the size of the chair component, and may vary between one and three hours. Dunnigan (1985, p. 60) refers to the need for careful plasticising time. The author affirms that if plasticising time is short, then the wood fibres will crack on the outside surface due to the inability to hold tension forces; and if plasticising time is long, then the wood fibres will crack on the inside surface due to compression forces.

Whereas these procedures relate to the preparation stage, the following are directly related to the shaping stage, in the specific case, of the back-rear leg unit. The operation is manual and is

[17] The parameters are retrieved from Thompson's description. There are minor differences in time and pressure parameters in Thompson and Dunnigan's information. This is due to the fact that the American factory uses elm and ash and the German factory uses beech.

The present description is complemented by analysis of a video of Thonet workers performing the bending activity (theemeraldbelt, 2013).

carried out by a team of two workers in a coordinated way. Dunnigan states that the wood loses its plastic behaviour in less than three minutes after being removed from the retort.

The bending procedures start with workers removing the plasticised wood from the retorts (Figure 39-3) and setting up the rod in the bending apparatus, which is an iron-cast mould (Figure 39-4). During this step they assemble a steel strap clamped to both ends of the rod. The strap is twisted to follow the convex side of the wood fibres, preventing them from stretching and cracking due to tension during the bending procedure. The rod is then centred and clamped to the top of the mould. The alignment is crucial because the rod is tapered at the top. To complete the initial clamping system, two additional clamps[18] are fastened: the first is positioned according to the changing direction of the metal strap and the second halfway between the one before and the end-clamp.

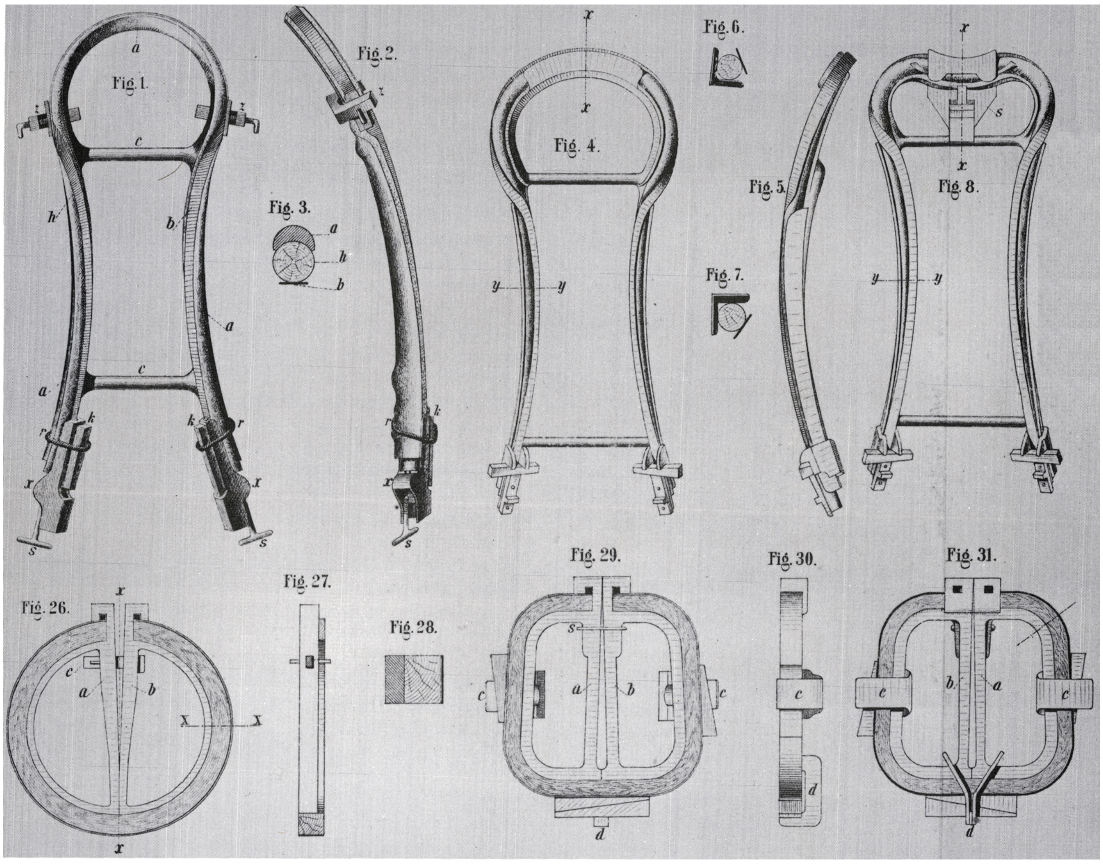

Figure 40. Iron moulds (produced by sand casting) for wood bending (Source: Wilk, 1980a, pp. 25–26)

The workers perform the operation by bending and twisting the wood onto the mould and clamping it to secure its position. The bending occurs in two cycles. The first cycle is the bending of the top area, which follows the characteristics of a single plane bending. The wood is secured by two clamps. The critical step is characterised by the small radius of the return curve. The

[18] The procedure is symmetrical. For simplification purposes the description focuses a single side.

second cycle (Figure 39-5) is the bending and twisting of the wood to achieve the change in plane direction and therefore the three-dimensional shape. At the end of this step, the wood is also secured by two clamps.

A metal shim is inserted between the wood and the end block to increase fitness conformance between the mould and bent component (Peck, 1957, p. 15). After this step, the clamps are removed, since Thonet moulds contain an optimised geometry with embedded fixture devices to maintain the wooden rod in the mould (Figure 40). The loaded mould is set in a drying chamber to stabilize the wood moisture level until it reaches 8%. This stage of the method can take up to forty-eight hours in an 80ºC chamber. When this stage is complete, the bent component is removed from the mould and the mould is reused.

The component is machined, sanded and stained, then assembled with the remaining chair components.

4.2.2. Design Style

The design style of Thonet chairs synthesized several influences from different periods, as previously mentioned. Moreover, the style resulted from the developing relationship between production methods and aesthetic purpose. The rationale of the industrialised process dictated the modular product architecture, the kit assembly principle and the reduced number of components, which are the main features of the chairs.

The basic Thonet chair structure[19] includes the following components: back-rear leg unit, back insert, front legs, leg brace, and seat frame. The Thonet chair style is characterised by its light and elegant structure. The back-rear leg unit is made using a single profile, with an organic shape. The profile is circular, with a variable cross-section that is thicker in the seat frame connection area and narrower in the crest rail area. From the front, this component rises from the bottom in a delicate curve that is narrower in the seat and reaches its full width at the change in curvature from the side rail to the crest rail area. When observed sideways, there is also a curvature which is more pronounced in the crest rail area.

The seat shape was circular in the first sets of versions, and either circular or trapezoidal from the beginning of the 20th century onwards (Thonet Company, 1980). The seat support panel is either made of woven cane or laminated veneer[20]. Contemporary specifications include upholstered seats covered with leather or fabric.

The distinguishing feature between models is the design of the back insert. It is defined by the use of one or two profiles, bent in symmetrically configured oval or "S" shapes. Laminated

[19] Although Gebrüder Thonet designed several chair models, remainder of this thesis refers to "Thonet chairs" as the ones in which the back-rear leg unit is a single component. Moreover, the hooped stretcher rail is considered the only leg brace, thus excluding other variations of this component (for instance, the 1911 catalogue displayed fourteen different types of leg braces (Wilk, 1980a, p. 75).)

[20] The seat panel in laminated veneer was introduced in 1888. The term laminated veneer refers here to all types of panel made with veneers, including plywood (developed in the 20th century), a type of laminated veneer in which the veneers are layered perpendicularly to each other.

veneers may be used in their construction, depending on the curvature and the diameter of the insert. The back insert can be connected to the back-rear leg unit or to the back-rear leg unit and seat frame. This principle allows for the configuration of several designs, which can be categorised into three types: simple chairs which follow the description above, reinforced chairs, and armchairs. 'Reinforced chairs' describe chairs with connections between the backrest area and the seat frame, and can be divided into two types of configurations: a) 'simple chairs' with an additional rod connecting the back-rear leg unit to the seat frame; b) chairs with a distinct frame structure in which the rear legs merge with the back insert. In this type of configuration, the reinforcement is a single bent rod that merges with the side and crest rails and connects to both the seat frame and the back insert-rear leg unit, providing the required reinforcement.

'Armchair' characterises both configurations of armchairs, whose components are configured as in the types described in 'reinforced chairs'.

4.2.3. Marketing Approach

Catalogues were the marketing device used to establish contact with potential consumers. As previously mentioned, they were issued in different languages. The first known catalogue was published in 1859 and displayed twenty-six designs in a broadsheet; in the years that followed, catalogues were expanded to publications containing several pages. The 30-page 1888 catalogue illustrated 348 items, the 1895 catalogue displayed 848 items in 120 pages, and in 1904 a total of 1270 items were illustrated (Wilk, 1980b). By 1904, Gebrüder Thonet was producing over one million items per year in its seven factories.

From an analysis of the catalogues it is possible to track the evolution of the company and also the social context. Over the years, the catalogues began to display furniture for hospitals, theatres, churches, barber shops and schools, for instance. Moreover, new items were introduced specifically for home furnishing, including music stands, chess tables, magazine racks, bookshelves and towel racks.

The development of furniture for different budgets can also be observed, thus appealing to a very broad public. This led to new configurations and designs using simplified production methods. It also led to the development of furniture reflecting particular styles, such as historical revivalisms or the contemporary Jugendstil, Viennese Secession and Art Nouveau.

The growing number of typologies was accompanied by a greater range of sizes, finishes and extra options (Figure 41). As an example, the 1888 catalogue introduced the option of selecting laminated veneer as a seat panel in some models (Wilk, 1980a), which became a standard option from 1895 onwards.

Apart from the pages displaying the designs, the catalogues contained a preface with useful information about the terms and conditions for buying and shipping items. The information included numbering, dimensions, possible variations of a model, types of finishing, and prices.

Moreover, aspects of the bentwood method and other manufacturing principles were explained, as well as the assembly instructions, spare components and maintenance procedures.

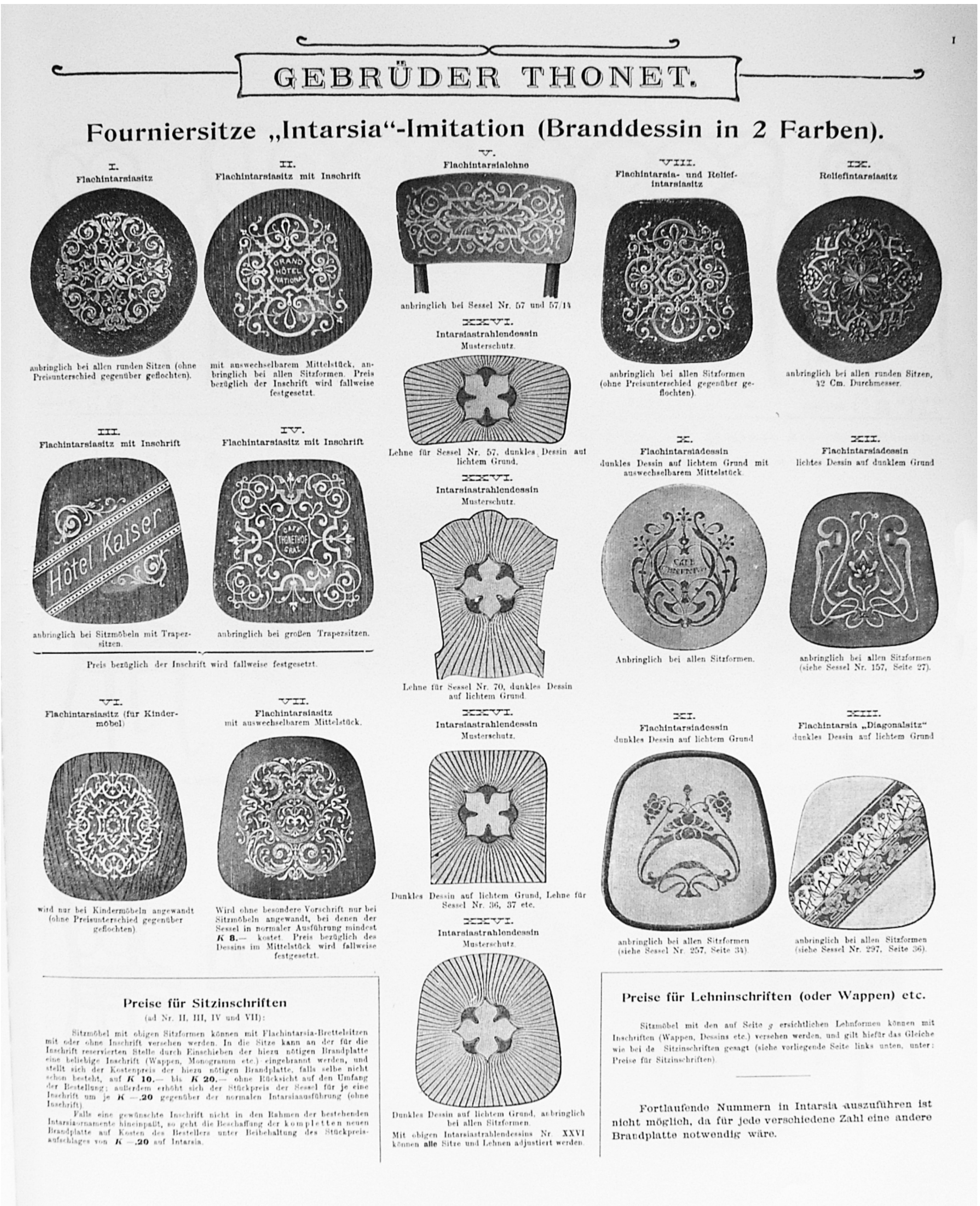

Figure 41. Page from the 1904 Catalogue displaying finishing options for the seat panel (Source: Thonet Company, 1980, p. I)

4.3. Thonet's Legacy

4.3.1. Contemporary Evolution of the Design Style

On the 150th anniversary of Chair No.14, a redesign was launched[21], developed by a partnership between Thonet GmbH[22] and MUJI. The redesign project comprised the chair and a table. James Irvine, who was Thonet's creative director, was responsible for the project.

The chair (Figure 42) maintains the trapezoidal-shaped seat, which has been the default configuration for contemporary specifications. The optional support materials remain woven cane or laminated veneer (plywood.) The redesign consists of removing the leg brace and creating a new shape for the back insert, defined in moulded plywood. When placed in front of a table, this makes the chair almost invisible, due to the alignment of the back insert and the table top. The goal is to enhance the visible silhouette of the back-rear leg unit, which is a distinctive feature of the original Thonet design.

Figure 42. MUJI No.14 (Source: Wallpaper, 2009)

Name	MUJI No.14
Designer	James Irvine (1958-2013)
Producer	Thonet GmbH for MUJI (2009)
Development	2008-2009
Materials	Solid beech wood, plywood
Size (mm)	height 850, width 415, depth 550

[21] The redesign was initially presented in Tokyo Design Week 2008, although launched in Europe in 2009, according to Dezeen (Ziari, 2009).

[22] Gebrüder Thonet became a global company with several factories, branch offices and showrooms. In 1922 it was merged with the largest competitors, thus becoming Thonet-Kohn-Mundus. According to Wilk (1980a, p.83) there are several designations for the merged organisation. After World War II some delegations became autonomous, thereby creating several companies which own the rights to produce according to the original specifications. Since that period Gebrüder Thonet, now Thonet GmbH, is the family-held company located in Frankenberg, Germany. For simplification reasons, Thonet's company refers here to the organisation after the merger.

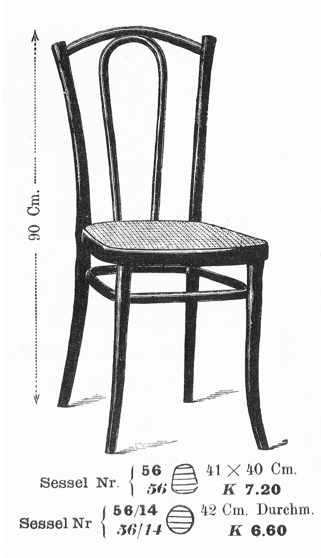

Figure 43. Chair No.56 (Source: Wilk, 1980a, p. 51)

Name	Chair No.56
Designer	August Thonet (1829-1910)
Producer	Gebrüder Thonet (1885)
Materials	Beech wood, woven cane seat
Size (mm)	height 900, seat width 410, seat depth 400

According to Wilk (1980a, p. 49), the task of simplifying the production method for the back-rear leg unit was accomplished in 1885 with the Chair No.56 series (Figure 43). The component was divided into three parts: two rear leg-side rails and one crest rail.

In 2011 Robert Stadler redesigned Chair No.14 with the aim of optimising it for contemporary production methods (Figure 44).

"My starting point was the fact that today chair 214 (historically named "N° 14") is now rather expensive, which represents a break with Thonet's history (...). With chair 107, I focussed on a new design for that section, which is now produced using an almost totally automated process" (Sadler, 2014).

The seat frame follows the trapezoidal shape verified in contemporary specifications. The remaining components represent a break with the original No.14 archetype. The former back-rear leg unit is now divided into five components: two independent rear legs, two connectors and a top panel which serves as the backrest support. The backrest support is made of plywood and displays the silhouette of the crest rail area and the back insert of an original No.14. This component is supported by two connectors, one on each side. The connector profiles are D-shaped and join the backrest support, the seat frame, and the rear legs. The rear legs connect to the base of the seat frame. The front legs do not display the tapered shape observed in more contemporary versions. All the leg profiles are D-shaped.

The chair preserves the goal of creating a design composed of components that are both construction elements and design features.

Figure 44. Chair No.107 (Source: Sadler, 2014; Thonet GmbH, 2014b)

Name	Chair No.107
Designer	Robert Stadler (1966-)
Producer	Thonet GmbH (2011)
Materials	Beech wood
Size (mm)	height 850, seat height, 470, seat width 430, seat depth 390

4.3.2. Thonet's Influence on Chair Design

The Thonet company continued to develop innovative processes and designs. The approach was extended to other materials, such as the pioneering development of tubular steel furniture in 1929, two years after the first public exhibition of this type of furniture (Wilk, 1980a, p. 98), although the company did not invent this production method (Máčel, 1990). Designs by Marcel Breuer, Mies Van der Rohe and the design team composed of Charlotte Perriand, Pierre Jeanneret and Le Corbusier were produced by Thonet's company.

The legacy of Thonet's company is still present in furniture design, reflected in several principles which can be summarised as experimentation as a process, design style, production principles, and marketing.

4.3.2.1. Experimentation as a Process

The thorough experimentation with wood bending influenced generations of designers. The research into laminated veneering undertaken at Gebrüder Thonet in the 1870s and 1880s (Figure 45) directly influenced experimentation with plywood in the late 1920s. The commercial availability of synthetic-based adhesives supported the development of plywood furniture. The Beugelstoel, developed by Gerrit Rietveld in 1927 (Figure 46a), and Alvar Aalto's Model No.F35, produced in 1930 (Figure 46b), are the first examples of the application of this production method to larger surfaces. Apart from commercially produced furniture, Alvar Aalto's exhibitions in London in 1933 (Design Museum, 2014), and in New York in 1938 (MoMA, 2014a), had a great influence on the dissemination of this production method in furniture design.

The original method of bending wood still influences contemporary generations. In 2009 François Dumas (2010) transposed Thonet's wood bending principles to thermoform plastic in the Sealed Chair series (Figure 47).

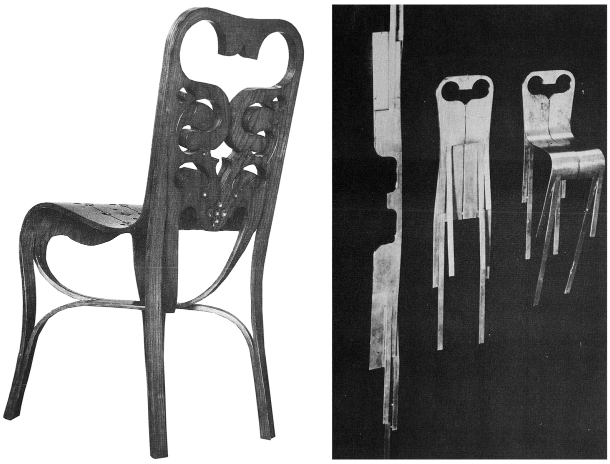

Figure 45. Laminated veneer chair, ca. 1880. Scale model of the construction stages.
(Source: Wilk, 1980a, p. 48-49)

Figure 46. First chairs using plywood to construct an integrated seat-backrest support
(Source: a) Design Art News, 2014; Fiell & Fiell, 2001, p. 195; b) (MoMA, 2014b)

Name	Beugelstoel
Designer	Gerrit Rietveld (1888-1964)
Manufacturer	Metz & Co., The Netherlands (from 1930)
Development	1927
Materials	Painted moulded bentwood and tubular steel
Size (mm)	height 600, width 400, depth 600

Name	Model No.F35
Designer	Alvar Aalto (1898-1976)
Manufacturer	Huonekalu-ja Rakennustyötehdas Abö Turku, Finland (1930)
Development	1930
Materials	Moulded plywood and chrome-plated tubular steel
Size (mm)	height 795, width 550, depth 640

Figure 47. Sealed chair (Source: Designboom, 2010; Dumas, 2011)

Name	Sealed chair
Designer	François Dumas
Manufacturer	Self-produced (2009)
Materials	Moulded plastic rods

4.3.2.2. Design Style

Thonet's exploration of possible designs made from bentwood rods extended across several typologies. Therefore, designs which employ similar techniques or principles are often perceived as redesigns of Thonet's original bentwood designs. Adolf Loos' 1898 chair for the Café Museum (Figure 48), produced by Kohn in Vienna, can be interpreted as a redesign of Chair No.14. The chair displays a different structure: the one used in Thonet's reinforced chairs. The back insert area is laminated and blends with the solid bent rear legs. The profiles' shapes present diameter variations which create a distinctive look.

Nendo's 2013 chair produced by Akimoku is a redesign of the Thonet armchair B9, presented in the 1904 Catalogue (Figure 49). The difference lies in replacing the hooped stretcher rail with three straight stretcher rails.

Figure 48. Chair for the Café Museum (Source: MAK, 2014)

Name	Chair for the Café Museum
Designer	Adolf Loos (1870-1933)
Manufacturer	J&J Kohn, Austria (1898)
Materials	Beech wood, woven cane seat
Size (mm)	height 880, width 405, depth 420, seat height 470

Figure 49. a) Chair No.508 EB; b) Armchair B9 (Source: a) Yoshida, 2013; b) Thonet GmbH, 2014a).

Name	No.508 EB
Designer	Nendo (1977-)
Manufacturer	Akimiku for IDC Otsuka (2013)
Materials	Beech wood

Name	Armchair B9
Designer	Attributed to August Thonet
Manufacturer	Gebrüder Thonet (1900)
Materials	Beech wood

4.3.2.3. Production Principles

The industrial production dimension of Gebrüder Thonet also influenced the methodology and the division of labour in the furniture industry. Furthermore, the principles of standardisation and the use of interchangeable components to create different versions are still used in the industry. Depending on the type of product and typology, there are different trade-offs between manual labour and automatic machinery. In the furniture industry, the principles of mass production, such as those defined by the introduction of the automatic assembly line, are mainly used in the office furniture and domestic panel-based furniture industries.

4.3.2.4. Marketing

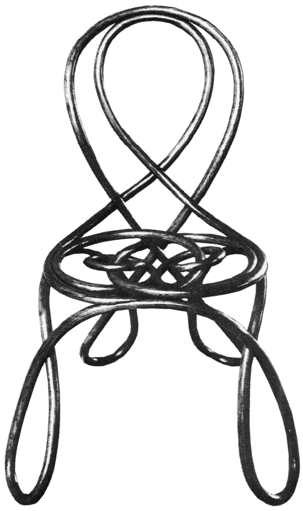

Figure 50. Concept chair, attributed to August Thonet, ca. 1867 (Source: Dunnigan, 1985, p. 56)

Thonet's approach to marketing is still evident in the contemporary furniture industry. Michael Thonet, and later his company, participated in exhibitions as a means of achieving recognition and establishing new contacts for marketing furniture. The preparation for fairs sometimes involved developing concept furniture, which was not produced but served the purpose of demonstrating manufacturing capabilities. The chair shown in Figure 50, made out of two beech wood profiles, is a concept chair developed for the 1867 Universal Exhibition in Paris.

Contact with distributors and end users took the form of publishing catalogues and opening offices and showrooms in different cities.

It is possible to transpose these principles to the contemporary furniture industry. Fairs have become specialized for the furniture trade and typology (CSIL, 2014), but the goals remain the same. In terms of making contact with distributers and end users, Thonet's principles are still observable, albeit with the necessary changes required by digital media.

4.4. Selected Corpus for the Case Study

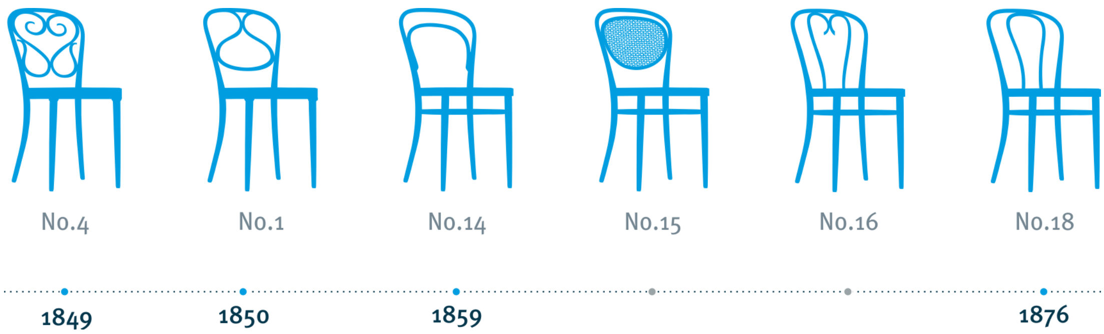

Figure 51. Chronology of Thonet chairs

The Thonet chair shape grammar was developed from a selection of existing chairs representative of the style developed initially by Michael Thonet himself and, after his death in 1871, the company. The six chairs were selected to represent different perceivable chair designs within the style (Figure 51).

Chair No.4 was the first to embody the features of the Thonet design style at a stage in its development that allowed for batch production, for the Café Daum in 1849.

Chair No.1[23], possibly designed before that date, but completed in 1850 for the Palais Schwarzenberg, displays a greater level of simplification. The back insert is still made in "S" shaped laminated veneers, although with fewer curves. Both No.4 and No.1 represent the experimentation period and were lately refined for industrial production.

Chair No.14 is the most successful example of furniture design and the greatest expression of Thonet's experiments in mass production. Chair No.15 is a direct variation on No.14, displaying a closed hoop in the back insert. This particular feature offered the possibility of selecting material for the enclosed area, such as woven cane or laminated veneer.

Chair No.18 was the second best-selling item after Chair No.14 and has been "the most important model designed after the death of Michael Thonet" (Wilk, 1980a, p. 43). This model is the first to display the back insert connected to both the seat frame and the back-rear leg unit.

Chair No. 16[24] is a non-optimised variation of Chair No.18, employing two back inserts, a feature that can be observed in the earlier Chair No.4.

The selection of the corpus is summarised by the following conditions: two early designs, two best-selling designs and two variations on optimised designs.

[23] Following the numbering system for the chairs, Chair No.1 was probably designed before No.4, although it was produced after.

[24] Chair No.16 is not featured in the accessed catalogues. Following the numbering system, it was designed before the No.18 chair. Chair No.16 is now developed commercially by the TON company, in the Czech Republic.

After the chairs were selected for the corpus, the next step towards developing the shape grammar was empirical analysis based on a formal description of the chairs (Section 4.2.2). The description identifies the number of structural profiles, their relative position, the number of connections between them, and the characterisation of the back inserts, which is crucial to guaranteeing structural stability in the back-rear leg unit. Subsequently, the corpus was analysed to determine the essential spatial relations between these elements, concluding that pairs 'No.1–No.4', 'No.14–No.15' and 'No.16–No.18' shared similar features in terms of the design of the back insert and its connection to other components. Table 3 summarises the analysis of the tacit knowledge embedded in the designs.

No.1	Five components: back-rear leg unit, single back insert, seat frame and two front legs. **1. Back-rear leg unit** Material/production method: Although it appears to be a unique bent rod, it was produced using two bent pieces for the legs and laminated veneer for the crest rail (Alverà, 1987). **2. Back insert** Shape configuration: Double "S" shape symmetrically creating a single element. Connection to back-rear leg unit: Four areas, two in the top area and two on the side. Connection within the back insert: Single point on symmetry axis. Material/production method: Laminated veneer. **3. Seat** Shape configuration: Trapezoidal. Supporting panel: Woven cane. **4+5. Front legs**
No.4	Six components: back-rear leg unit, two back inserts, seat frame and two front legs. **1. Back-rear leg unit** Material/production method: Same as No.1. **2+3. Back inserts** Shape configuration: Symmetrical double "S" shape. Independent elements. Connection to back-rear leg unit: Each insert connects in two areas, one on the top and one in the side area. Connection between back inserts: Two points. Connection within the back insert: One point. Material / production method: Laminated veneer (mahogany.) **4. Seat** Shape configuration: Trapezoidal. Supporting panel: Upholstered. **5+6. Front legs**

No.14 Six components: back-rear leg unit, single back insert, seat frame, two front legs, leg brace (hooped stretcher rail.)

1. Back-rear leg unit

Material/production method: Single bent rod. Tapered. Beech wood.

2. Back insert

Shape configuration: Arched.

Connection to back-rear leg unit: Two points (screws) in each side.

Material/production method: Single bent rod. Beech wood.

3. Seat

Shape configuration: Circular.

Supporting panel: Woven cane.

4+5. Front legs

6. Leg brace

No.15 Six components: Same as No.14

1. Back-rear leg unit

Material/production method: Same as No.14.

2. Back insert

Shape configuration: Elliptical.

Connection to back-rear leg unit: Similar to No.14.

Material/production method: Same as No.14.

3. Seat

Same as No.14.

4+5. Front legs

6. Leg brace

No.16 Seven components: back-rear leg unit, two back inserts, seat frame, two front legs, leg brace (hooped stretcher rail.)

1. Back-rear leg unit

Material/production method: Same as No.14 and No.15.

2+3. Back insert

Shape configuration: Arched. Vertical. Mirrored elements.

Connection to back-rear leg unit: One point in the top area (per element.)

Connection to seat frame: One point (per element.)

Connection between back inserts: One point.

Material/production method: Single bent rod. Beech wood.

4. Seat

Shape configuration: Circular.

Supporting panel: Laminated veneer.

5+6. Front legs

7. Leg brace

No.18	Six components: back-rear leg unit, single back insert, seat frame, two front legs, leg brace (hooped stretcher rail.) **1. Back-rear leg unit** Material/production method: Same as No.14, No.15, and No.16. **2. Back insert** Shape configuration: Arched. Vertical. Connection to back-rear leg unit: One point in the top area. Connection to seat frame: Two points. Material / production method: Single bent rod. Beech wood. **3. Seat** Shape configuration: Circular. Supporting panel: Woven cane. **4+5. Front legs** **6. Leg brace**

Table 3. Analysis of the chairs in the corpus

4.5. Summary of the Chapter

This chapter presented the important role Michael Thonet and his company played in the development of furniture design. Its organisation aimed to offer a global perspective of the role of both the designer and manufacturer in shaping the furniture design industry. The description aimed to clarify the interconnected role between design features, production constraints, and marketing possibilities.

The initial experiments with wood bending (Section 4.1.1.) are mapped from their inception towards the establishment of the company and the respective large-scale batch production (Section 4.1.3.). Then, the chapter proceeds with an analysis of the Thonet design system (Section 4.2). It examines in detail the wood bending techniques, previously characterised in Section 2.4., applied to the production of a specific component of the Thonet chairs, the back-rear leg unit. Following the premises stated above, the section describes the design style (Section 4.2.2.) and the marketing approach (Section 4.2.3.).

The characterisation of Thonet's legacy (Section 4.3.) aimed to intertwine the historical facts with the continuous evolution of the design field until the present, under two perspectives. The first was the contemporary evolution of the Chair No.14, the iconic chair designed by Thonet in the 19th century. The second was the influence exerted by Thonet to the design field under the same topics in which the chapter was organised: experimentation, design style, production and marketing.

The chapter ends with the justification of the selection of the six chairs which constitute the corpus for the case study. In addition, the initial analysis regarding the aspects of design and production was systematised.

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5. The Generative Design System

5.1. Introduction

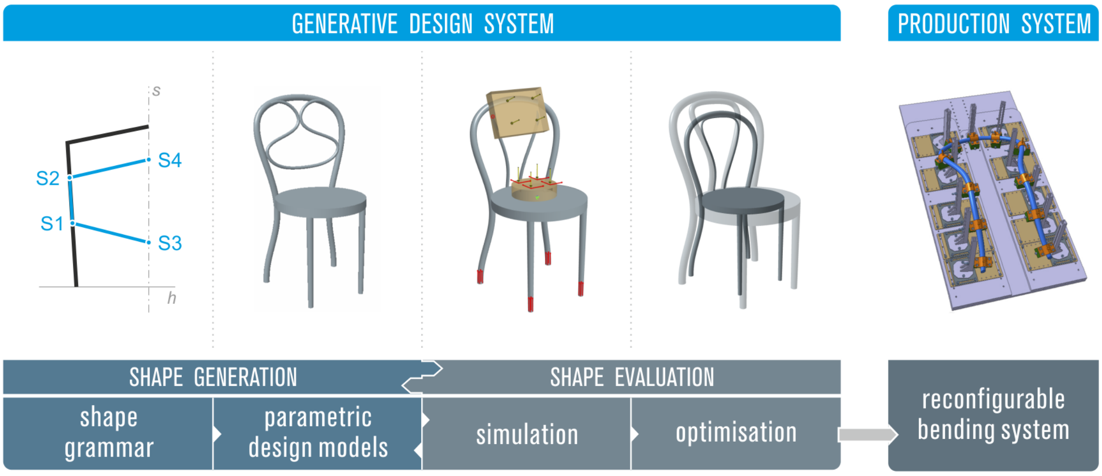


Figure 52. Proposed model for mass customisation in the furniture design industry

This chapter details the modelling activities for encoding the generative design system for mass customisation. The goal is to support the designer in defining, exploring and selecting a feasible structural solution that is part of a customisable design language. The ultimate goal is the automatic integration of all parts of the system to enable industrial application, and a link to a frontend application to enable customisation by an end user.

In comparison with the model of design process defined by Pahl et. al (2007), the generative design system can be characterised as the encoding of the embodiment design phase. The input for this phase of the design process is a principle solution or concept design and the output is a definitive layout optimised for production. The embodiment design phase can be summarised in two stages. The first aims to establish the preliminary layout, which require definition of shape and material attributes. Formal synthesis methods defined by Bonsiepe (1992, p. 221) are employed to create formal identity between different elements of a design in the case of a unique product, and between different designs in the creation of a product family. In the second stage, the preliminary layout must be analysed and optimised into the definitive layout, to enable production.

Transposing the goals of the embodiment design phase to mass customisation requires generating and customising the preliminary layouts within a design language and optimising them for production. For these reasons, the proposed generative design system encompasses two interconnected subsystems: shape generation and shape evaluation. Each subsystem consists of two parts.

Shape grammars (Section 5.2) are used to encode the existing design style and results from rule application are converted into equivalent parametric design models (Section 5.3) to allow for generation and the search for solutions. The customised variants generated by these parts become the input information for the shape evaluation subsystem, defined by the use of simulation (Section 5.4) and optimisation (Section 5.5.)

Figure 52 illustrates the model for mass customisation in the furniture design industry. The generative design system displays the different interconnecting subsystems and its constituent parts. The definition of the Thonet shape grammar is encoded as the first part of the generative design system. It is developed from a corpus of six chairs (Section 4.4) and generates several 'topological versions'. A topological version is a design solution created by the designer by manipulating rule application of the shape grammar.

In Figure 52, the unidirectional arrow that connects the shape grammar to the parametric design models indicates that the latter are developed by using the results from shape grammars as input. Each solution generated by the shape grammar – a topological version – is encoded as a different parametric design model, thus allowing for interactive exploration of the 'customised variants'. A customised variant is a parametric variant of a topological version. Parametric design models assist the designer in further exploration of solutions that meet individual user needs by assigning values to the parameters.

The digital data produced by the shape generation subsystem is linked to the shape evaluation subsystem. This subsystem acts upon previous information and is an iterative stage in the continuous flow of information from generation to production.

In Figure 52, the shape evaluation subsystem is connected to the shape generation subsystem by two arrows. The first displays the direct connection between the parametric design models and the simulation models. The reverse arrow indicates that the results from the shape evaluation are updated in the parametric design models, which serve as the central repository of digital information. The simulation part enables the structural behaviour of each customised variant to be analysed using FEM. In the event of failure, the optimisation part enables the computer to search for an optimal solution, considering a particular set of physical and material conditions.

5.2. Shape Grammar

This section describes the development of the Thonet shape grammar. The introductory subsection below contextualises the specific goals of the shape grammar, considering the general goals of the generative design system. The methods that define the shape grammar properties are then detailed. These methods are categorised as three main steps: representation simplification, algebras, and rules. The shape grammar results are presented according to the validation tests defined in the literature. The section concludes with a discussion of the results and the methods used to develop the shape grammar.

5.2.1. Introduction

"When a client asks a designer for 'a design', that is what they want: the description. The focus of all design activities is that end-point" (Cross, 2000, p. 4).

The ultimate goal of the generative design system is the customisation of a design by the final user. The designer must therefore systematise the "materials, components, structure and construction, as well as the overall form, shapes and functions" (Cross, 2000, p. 9) in a way that is amenable to generation.

The purpose of the shape grammar is to encode the Thonet chair design style into a design language that guides the generative design system. The Thonet design style comprises a set of design principles that is embedded in the corpus (Section 4.4). It is based on a modular strategy that relies on the interchangeability of components and focuses mainly on different designs for the back insert.

Considering the design principles developed by Thonet as primarily belonging to tacit knowledge, since they are not explicit for generative procedures nor mass customisation requirements, then, the aim of the shape grammar is to translate them into explicit knowledge. The goal is to translate the shape and material-related aspects into a set of rules that enable multiple design solutions to be generated, in addition to the corpus. This premise provides the means to define the design process for mass customisation in a way that extends beyond the discrete solutions permitted by the modular strategy, thus constituting a new strategy for the furniture design industry.

The shape grammar formalism is first used to capture the rules of formal composition for the Thonet design style and then to generate new designs through the creative application of these rules. Due to the wide variety of chairs designed by Thonet, six chairs (Section 4.4) were chosen to infer the grammar. The formal description presented in Section 4.4 and the similarities between pairs 'No.1–No.4', 'No.14–No.15' and 'No.16–No.18' are taken into account when inferring the shape grammar properties.

5.2.2. Simplification of the Representation

The Thonet shape grammar shares similarities with the Hepplewhite-style shape grammar (Knight, 1980). Both address the issues of encoding curvilinear shapes and focus on the chair back designs. The focus in this area comprises the 'outer frame' and the 'inner frame'[25], since the configuration and position of these elements are the key features of the style. For these reasons, the same guiding strategy and similar methods for constructing the shape grammar are used in this research. The subdivision strategy is employed here, since different topological versions share the same boundary, together with simplification of representation into two levels of abstraction. The first level involves the representation of chair elements as lines, and the second the simplification of curvilinear into rectilinear representation, together with the representation of half of the schema, due to its bilateral symmetry.

The front orthographic representation of the designs provides most of the information about the configuration of the different backrest components except the lateral curvature. Although lateral curvature information is important for the configuration of the chair as a whole, it is not crucial in this step of the design process for mass customisation. Therefore, the two-dimensional front representation provides the basis for defining the Thonet shape grammar schema (Figure 53).

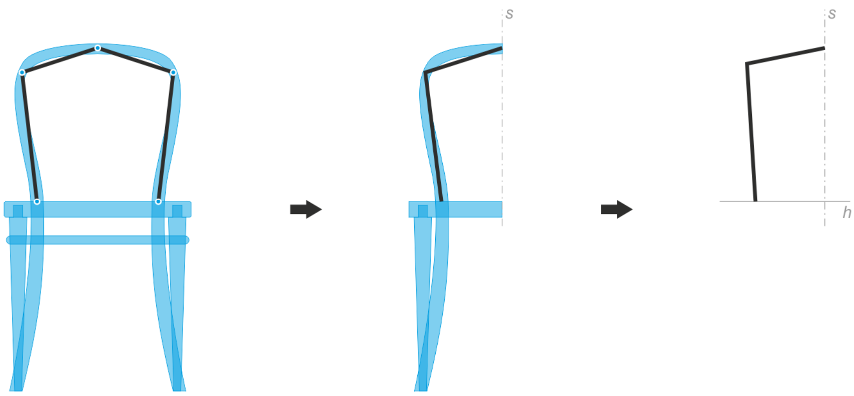


Figure 53. Steps in the simplification of the chair representation

Figure 53 shows the change in the level of abstraction from physical artefact to initial shape in the shape grammar. The initial shape is a simplified representation of the outer frame and is an element common to all the grammar rules. In order to control the positioning of subsequent elements, the initial shape also includes the axis of symmetry *s* and a horizontal segment *h* that indicates the position of the chair seat frame. An auxiliary 4 x 4 grid facilitates the understanding of the relative position of labels (points and segments), as shown in Figure 54.

[25] Since the shape grammar focuses on the backrest components, the terms outer frame and inner frame are used to provide a straightforward distinction between the back-rear leg unit and the back insert, respectively.

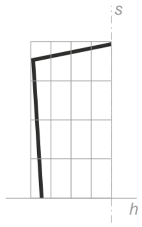


Figure 54. Initial shape with auxiliary grid

5.2.3. Algebras

ALGEBRAS	FUNCTION	GRAPHIC SYMBOLS	NAMING
U_{12}	Defines shapes in the Cartesian space		s h
V_{01}	Provides additional control for shape generation		A1 P1 P2 P3 P4 Q1 Q2 Q3 Q4 Q5 S1 S2 S3 S4
V_{12}	Establishes parametric space for variation		a’ a” a’” b’ b” b1’
W_{12}	Assigns different thickness to beech profiles		
W_{22}	Permits selection of materials for covering enclosed areas		

Table 4. Thonet shape grammar algebras

The proposed Thonet shape grammar is the Cartesian product of different algebras (Table 4). Algebras are applied according to the results of the description and analysis of the corpus. They constrain rule application by encoding functional requirements into the shape grammar. The variables defined in the algebras are the topological variation space, differentiation of diameters for profile turning and material selection. This type of information, embedded in the shape grammar properties, ensures that custom solutions conform to the stability behaviour embodied in the Thonet design style.

Shapes are defined in algebra U_{12}. The range of the connection between the inner and outer frames is defined in the labelled algebras V_{02} and V_{12}. Labelled algebra V_{02} controls most of the generation procedures, enabling points to be positioned within the established ranges. Labelled algebra W specifies material properties. W_{12} characterises the diameter variation in the beech profiles. The black segments have more weight than the cyan ones which, in turn, have more weight than the light blue ones. The black and cyan segments represent bendable wood profiles, whereas the light blue ones define elements that must be constructed from laminated veneers. Algebra W_{22} describes the selection of materials for the enclosed areas. The dark grey corresponds to laminated veneer and the light grey to woven cane.

5.2.4. Rules

As previously explained, the initial shape is a schematic representation of a half chair back. When the generation procedure is complete, the design must be reflected along the symmetry axis s to obtain the complete chair design. Following this, *s* and the horizontal segment *h* are removed.

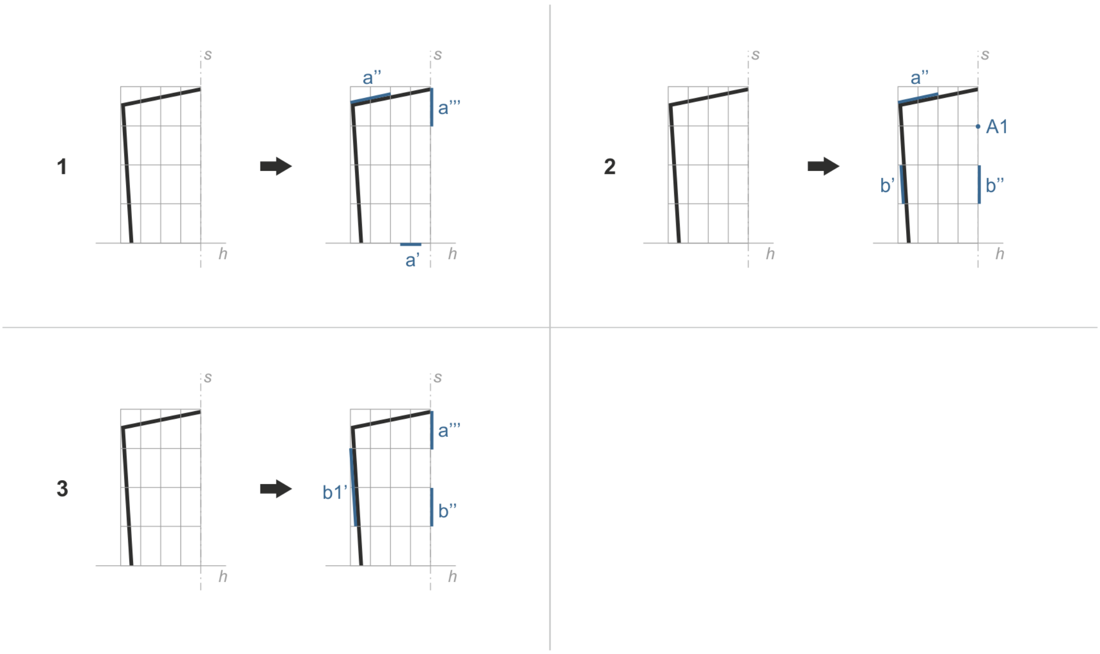


Figure 55. Rules 1 to 3

Rules 1 to 3 introduce the initial shape and enable three sets of labels to be defined. Figure 55 shows the rule application procedure superimposed on the auxiliary grid to inform the placement of labels. The placement of labels is described from bottom to top and from left to right. They comply with the following principles:

a' is a labelled segment embedded in the horizontal segment *h*. It starts at 5/8 of the grid width and its length is 1/4 of the grid width.

a'' is a labelled segment embedded in the outer frame. It starts at the frame turning point and it ends at 2/4 of the grid.

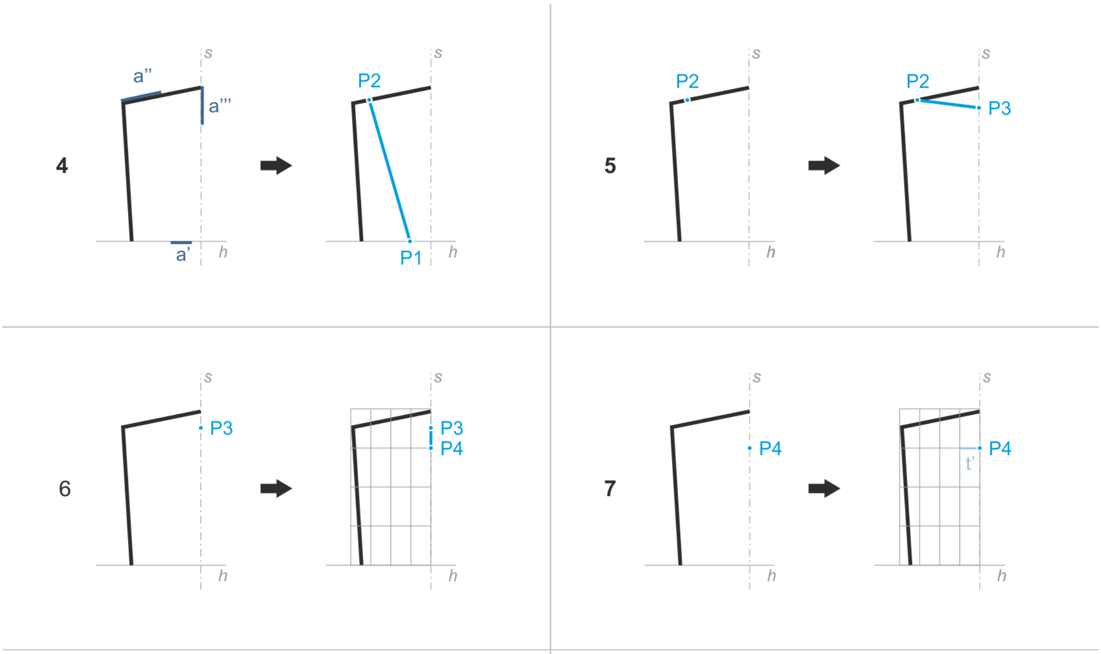
a''' is a labelled segment embedded in the symmetry axis *s*. Its length is 1/4 of the total height of the backrest.

b’ is a labelled segment embedded in the outer frame. It starts at 1/4 of the grid and its length is 1/4 of the total height of the backrest.

b” is a labelled segment embedded in the symmetry axis *s* with the equivalent position to segment b’.

b1’ is a labelled segment embedded in the outer frame. Its endpoints are located at 1/4 and 3/4 of the total height of the backrest.

A1 is a labelled point embedded in the symmetry axis *s* that is located at 3/4 of the total height of the backrest.



8 <sØ, {(0,0): P1, (0,0): P2, (0,0): P3}> → <sØ, Ø>

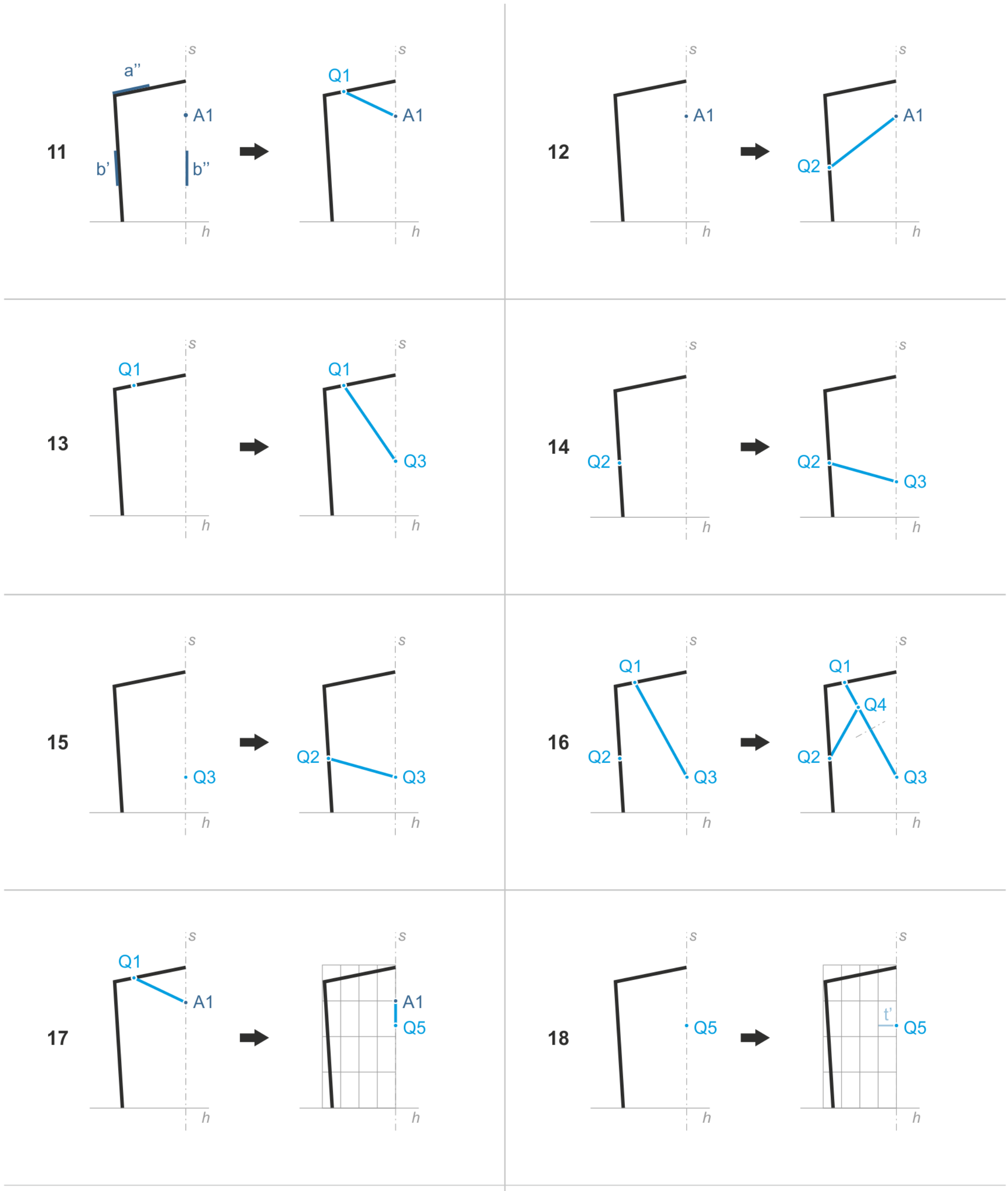
9 <sØ, {(0,0): P4}> → <sØ, Ø>

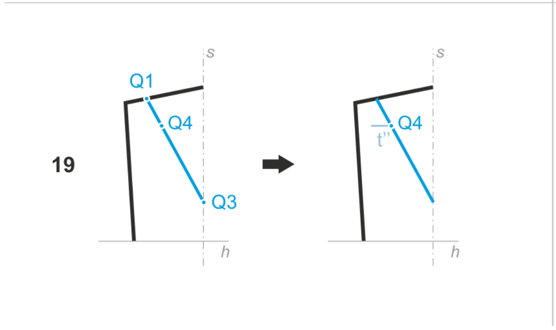
10 <sØ, {(0,0): t’}> → <sØ, Ø>

Figure 56. Rules 4 to 10

Rule 1 allows for the application of Rules 4 to 10 (Figure 56). In this set of rules, all points will be embedded in one of the labelled segments a’, a”, or a’”. The application of Rule 7 enables a less weighted segment t’ to be added, whose length is 1/4 of the width of the grid.

Rules 8 to 10 remove labelled points. Rule 8 constrains the removal of labelled points when the shape has at least points P1, P2 and P3. This type of rule prevents the generation of an incomplete inner frame, thus ensuring that the functional requirements of providing support for the user and resilience for the outer frame are met.





20 <sØ, {(0,0): A1, (0,0): Q1}> → <sØ, Ø>

21 <sØ, {(0,0): Q2}> → <sØ, Ø>

22 <sØ, {(0,0): Q3}> → <sØ, Ø>

23 <sØ, {(0,0): Q4}> → <sØ, Ø>

24 <sØ, {(0,0): Q5}> → <sØ, Ø>

25 <sØ, {(0,0): t''}> → <sØ, Ø>

Figure 57. Rules 11 to 25

Rules 11 to 25 (Figure 57) can be applied after Rule 2 has been used. Points Q1, Q2, Q3, and Q5 are the points of connection between the inner and outer frames and can only be embedded in any of the labelled segments a”, b’ and b”. Point Q4 can only be positioned in the top half of the segment Q1-Q3.

Rules 20 to 25 permit the removal of labelled points, allowing for the generation of chairs like No.1 and No.4. Rule 20 follows the same principle as Rule 8, determining the removal of three points at once to enable the generation of functional inner frames.

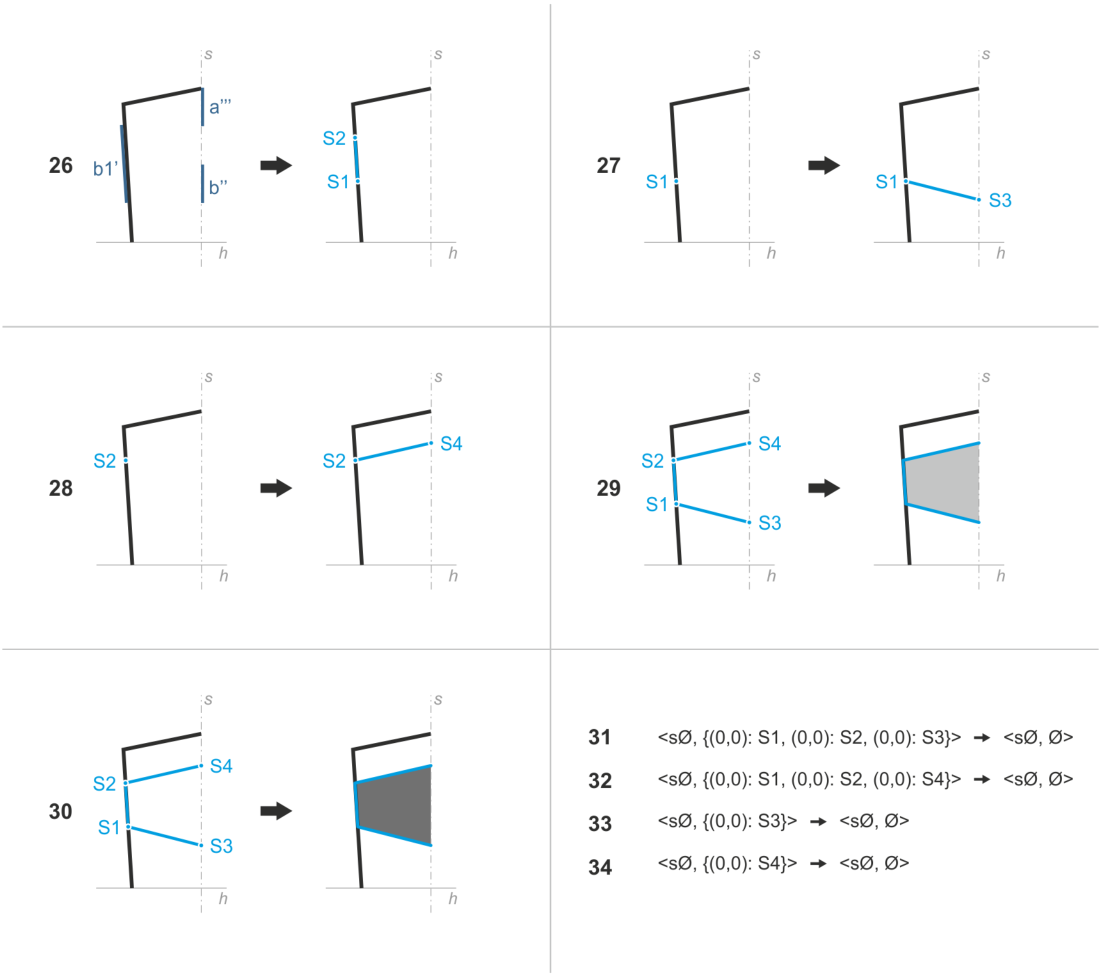


Figure 58. Rules 26 to 34

Rules 26 to 34 (Figure 58) can be applied after Rule 3 has been used. Points S1, S2, S3, and S4 can only be positioned in the labelled segments a’”, b” and b1’.

Rules 29 and 30 can be used to specify the material for the enclosed area of the inner frame. Rule 29 determines woven cane and Rule 30 laminated veneer.

The application of Rules 31 to 34 erases labelled points. Like Rules 8 and 20, Rule 31 permits the removal of a set of points at once.

5.2.5. Validation Tests

A shape grammar defines a design language when it fulfils three types of tests (Stiny & Mitchell, 1978): the descriptive, the analytic and the synthetic. Duarte (2001, p. 38) synthesises the tests as follows.

"Descriptive test: can the grammar generate designs in the corpus?
Analytic test: can the grammar generate existing designs not in the original corpus?
Synthetic test: can the grammar generate new designs in the style?"

5.2.5.1. Descriptive Test

Figure 59 shows the key steps in the generation of chairs in the corpus according to the proposed shape grammar. The first step branches off into three different design families, each characterised by the style of the connection between the backrest components, as defined in the first three rules.

The first family, depicted on the left, comprises two connection points in the side area of the outer frame. There can be either one or two connection points on the symmetry axis. This leads to the generation of chairs No.14 and No.15, respectively. If the central element is closed, there is an option to select a material to define a support panel.

The distinguishing feature in the second family is the existence of symmetrical "S" shapes. In this family, there are four connection points: one in the top area of the outer frame, one in the side area of the outer frame, and two connection points on the symmetry axis. Chair No.4 has two separate inner frames. Chair No.1 has one, achieved by merging the lower point in the symmetry axis.

The third family is characterised by one connection element between the seat frame and the top area of the outer frame and another between the top area of the outer frame and the symmetry axis. It generates Chairs No.16 and No.18.

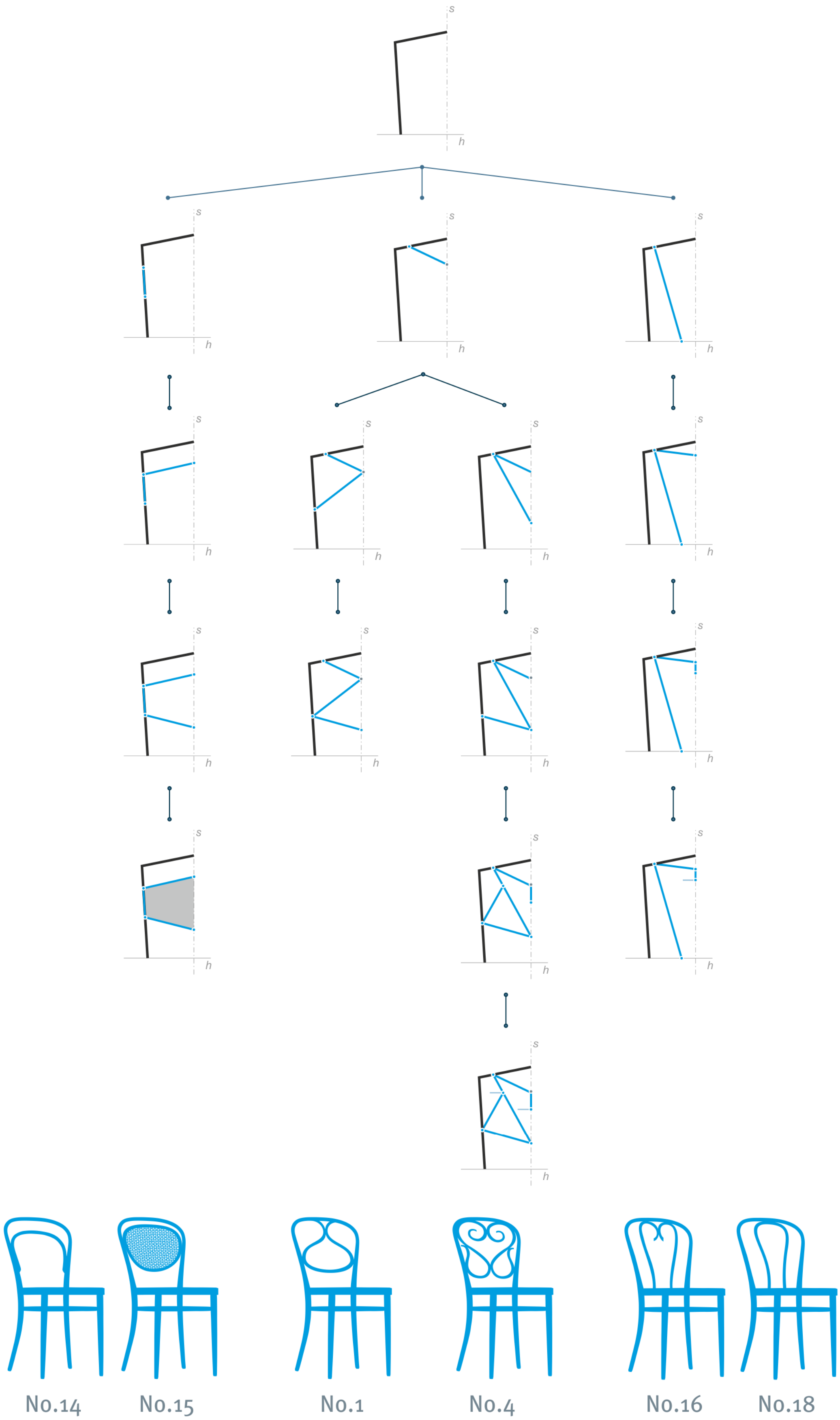


Figure 59. Tree diagram showing the key steps in the generation of chairs in the corpus

5.2.5.2. Analytic Test

The analytic test determines whether the grammar can generate Thonet designs that were not selected in the corpus. The shape grammar creates variants of Chair No.15 by selecting weights as options to define support panels. Although this condition enables the analytical test to be validated, it is still a modular strategy.

The creative use of rules leads to the generation of a design similar to Chair No.20 (Figure 60), which was designed in around 1870 (Bangert & Ellenberg, 1997, p. 39). Figure 61 shows the derivation of a topological version that is similar to Chair No.20. However, the rules cannot generate Chair No.20 precisely due to the fixed labelled point A1. This condition determines the possibility of improving the rules.

Figure 60. Chair No.20, ca. 1870 (Source: Bangert & Ellenberg, 1997, p. 39)

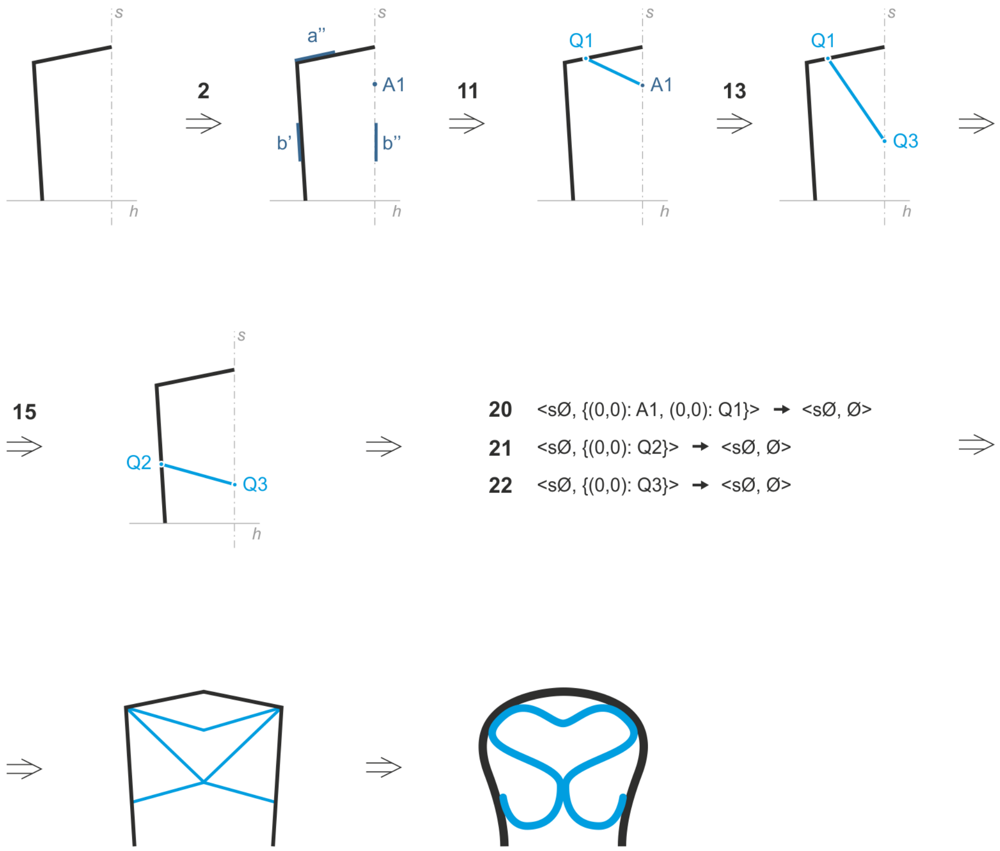


Figure 61. Generation of a topological version similar to Chair No.20

5.2.5.3. Synthetic Test

The synthetic test determines whether the shape grammar is able to generate new designs in the Thonet chair design style. Creative application of the shape grammar rules allows for the generation of new chairs not included in the corpus. Figure 62 shows a sample of new designs generated from the grammar. Intersecting profiles, achieved by interpreting the embedding segments, are shown in orange.

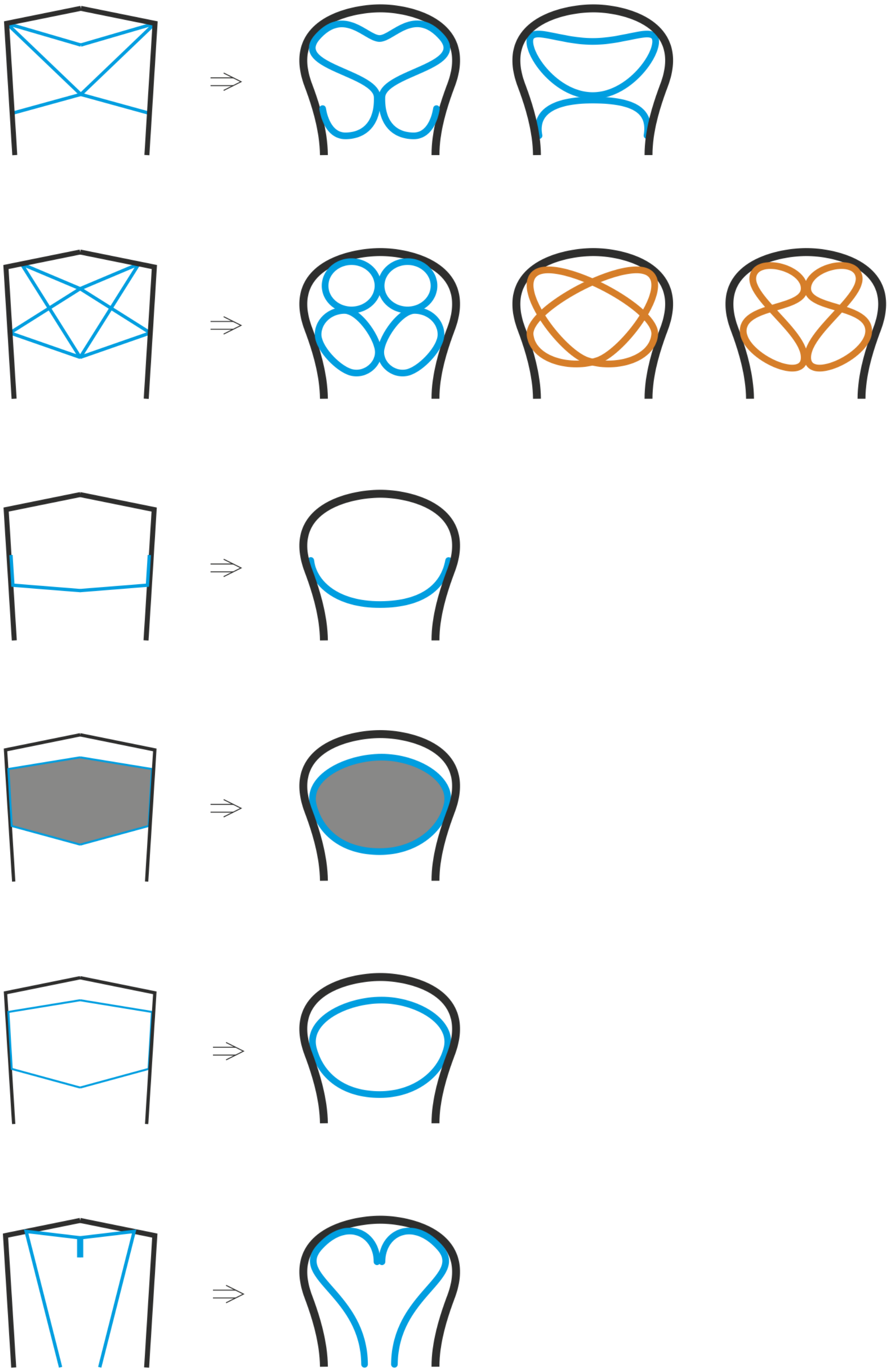


Figure 62. New designs generated by applying the rules

5.2.6. Discussion

"(...) there is something mysterious about the human ability to propose a design for a new (or even just a modified) artefact. It is perhaps as mysterious as the human ability to speak a new sentence, whether it is completely new, or just a modification of one heard, read or spoken before. This ability to design depends partly on being able to visualize something internally, in 'the mind's eye', but perhaps it depends even more on being able to make external visualizations" (Cross, 2000, p. 9).

In conventional design methodologies, the output of the design process is a single solution. Technical drawing is the representation medium employed to describe and enable the generation of instances of the same solution.

The goal of the generative design system is to guarantee 'external visualisation' of the underlying principles of the design style in order to enable different solutions to be generated which conform to a single design language[26]. Shape grammar is the generation mechanism that enables shape computation. The explanation of a step-by-step formation of the designs formalises the properties for the design language and establishes the solution space according to the specifications defined by the designer.

The Thonet shape grammar comprises thirty-four rules. In addition to the corpus, it provides the means to create at least nine new designs that could be defined as part of the language. Appendix 1 contains the complete derivation of all designs generated by the shape grammar. The designs were classified under three main design families, each characterised by the style of the connection between the backrest elements: the outer frame, the inner frame(s), and the seat frame.

The reduction of the number of rules is directly related to simplification of representation, accomplished by establishing two levels of abstraction. The rules operate on a higher level of abstraction, dealing essentially with the position of points to define a topological solution. Therefore the interpretation of curvilinear geometry, such as circles, arcs of circles or ellipses, is left to a post-processing step which is decoupled from rule application. As previously mentioned, the use of such a level of abstraction follows the principles applied by Terry Knight in the Hepplewhite-style shape grammar. However, the abstraction of curves into rectilinear elements is a design method that has been used on other occasions. In 1925 Paul Klee described this type of simplification as the limitation of the movement of an active line (curve) by using fixed points (1972 [1925], p. 18). A similar approach can be found in three-dimensional graphics. Curvilinear shapes are modelled in low-polygonal meshes to reduce complexity of representation (and the computation resources required) before subdivision algorithms determine the final smooth mesh (Russo, 2006).

[26] The terms 'design style' and 'design language' are often used to characterise similar concepts. In this thesis 'design style' is used to characterise the relations of similarity observable in the Thonet chairs. 'Design language' refers to the set of designs generated by the shape grammar (Section 1.5).

In the case of the Thonet shape grammar, the curve is subdivided with a single control point. This approach was adopted after assessing the different types of simplification methods and evaluating them in terms of the shape grammar goals. Simplification isolates complexity, leaving the shape grammar to deal only with design issues related to topology and material specification. The combination of these principles helps reduce the number of rules and this method of curve subdivision may be applied in the development of other objects which comprise curvilinear shapes. The method used here can be interpreted as the 'lowest resolution' one, describing curves with one point. Assessment of the appropriate 'resolution 'should consider the relationship between the components in the object that is being represented, the potential of the shape grammar to generate solutions, and the expected number of rules.

The shape grammar generates solutions with embedded segments, which can be translated into designs that contain intersecting profiles (Figure 62). Although Thonet designed inner frames (back inserts) using intersecting profiles, the production method was different and it required additional mastery. The principles for the construction of intersecting profiles involve thinner wooden veneers glued together and are more time-consuming than the standard method for bending solid beech wood rods. Following an analysis of this specific class of designs and the goals of the shape grammar, it was decided that the rules should be constrained in order to prevent this class of designs. Its inclusion would have required additional algebras W in order to comply with the variation in profile diameters. It would also have led to additional rules to determine the relative position of the profiles. The constraining takes place in the general considerations for rule application, stating that solutions cannot contain intersecting segments.

The definition of the shape grammar in this case study acts on information that has already been translated into physical artefacts. It is employed here as a means of encoding information that is usually defined using design methods, such as the formal synthesis methods (Bonsiepe, 1992, p. 221). Bonsiepe argues that the task of achieving aesthetic coherence lacks systematic methods and requires decisions concerning the coherence of elements or sets of elements, whether the goal is the design of a single product or a system of products. In the Thonet shape grammar, the analysis and rationalisation of tacit knowledge serves the purpose of encoding it as explicit knowledge. It makes the underlying principles of shape generation explicit and provides the means for generating other solutions within the design language. It becomes the guiding information for the generative design system, enabling a design language defined by a designer to be customised. In order to meet the requirement of assisting the designer in the exploration of custom solutions, the shape grammar must be encoded in CAD software.

The shape grammar formalism could be applied in earlier steps of the design process, in which the design language has not already been defined. In such cases, the development of the shape grammar would resemble the early steps of the Thonet shape grammar development which should, in turn, follow a methodology that involves defining vocabulary, spatial relations and rules, such as the one defined by Stiny for original shape grammars (1980, pp. 416–417).

The Thonet shape grammar defined in this section served the initial goals of the generative design system. The same principles may be extended to generate other Thonet seating typologies, such as armchairs, canapés and rocking chairs.

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5.3. Parametric Design Models

This section presents the parametric design models, from definition to implementation and from usage to refinement. First, the shape grammar interpretation illustrates the conversion into a parametric design rationale suitable for computer implementation. Secondly, the procedures for encoding parametric design models are presented, followed by the operational usage for the generation of customised variants. Rapid prototyping is explored as an instrumental step in the refinement process. The section concludes with a discussion which assesses the use of parametric design models as the second part of the shape generation subsystem and as a central information repository for the generative design system.

5.3.1. Introduction

The generative design system for the mass customisation of furniture comprises two interconnected subsystems: shape generation and shape evaluation. The digital information produced by the generative design system will guide the production system for manufacturing chair components.

The shape generation subsystem is characterised by the combined use of shape grammars and parametric design models. The Thonet shape grammar was developed in the initial step of the methodology and corresponds to the first part of the proposed mass customisation generative design system. It serves the purpose of formally describing the formation procedures for each design and characterising the underlying principles of the design style. Rule application enables similar topological versions that belong to the encoded design language to be generated. The computer implementation of the Thonet shape grammar serves to assist the designer in the interactive exploration of shape grammar solutions and in the selection of custom solutions.

According to the state of the art, shape grammar interpreters are quite limited in dealing with curvilinear shapes (Section 2.2.2.8). Furthermore, there are no interpreters available that include modules linking design outputs to CAM. Therefore, the direct computerised implementation of the Thonet shape grammar was impracticable.

An indirect type of implementation is possible through the use of existing CAD software, by converting the shape grammar results into equivalent parametric design models. From a shape exploration point of view, a parametric design model is more restrictive than a shape grammar interpreter, since the design generation does not occur by different rule application sequences. Despite the restrictive exploration issue, the ultimate goals of the case study must be considered: the production of a customised chair that belongs to a design language and complies with the required performance standards. Encoding the shape grammar into parametric design models overcomes such limitations, while providing a positive trade-off between design exploration and design goals. The parametric design models assist the designer in generating customised solutions according to the shape grammar rules.

Given the aforementioned premises, the shape grammar results were translated into equivalent parametric design schemas. The schemas are then encoded as parametric design models to support design exploration based on interdependencies established between the different geometric elements.

The shape generation subsystem addresses issues relating to the generation and exploration in the mass customisation generative design system. Parametric design models are the second part of the shape generation subsystem. Simultaneously, they are the first step in the digital design process, thus becoming the central data repository, generating information required in the subsequent parts of the generative design system and in the production system.

The parametric design models developed in this thesis are encoded in CATIA. The use of feature-based software with integrated analysis, performance and manufacturing workbenches[27] allows for the use of geometrical data required in subsequent steps of the design process and the mass customisation production process.

5.3.2. Shape Grammar Interpretation

The proposed shape grammar constitutes a higher level of abstraction of the encoded Thonet chair design style. Interpreting the shape grammars into parametric design requires procedures to: a) translate the parametric space defined in the shape grammar into a corresponding digital space for variation; b) translate the rectilinear symbolic representation used in the grammar into the curvilinear geometrical representation required for visualising the designs and producing the chairs.

The technique used to encode the parametric design models encompasses a straightforward interpretation of the syntactic structure of the Thonet shape grammar. For this reason, parametric design models comprise the shape grammar rectilinear representation, and its translation into a curvilinear representation is a built-in process. Although parametric design models do not require rectilinear representation to guide them, their inclusion provides the capacity to study a set of intermediate procedures in order to encode the translation from rectilinear schemas to curvilinear representation. This type of procedures is an important part of parametric design technique (Woodbury, 2010).

Implementation based on this technique requires an analysis of the properties of the shape grammar and the definition of an equivalent digital solution. Taking two rules from the generation procedure for Chair No.15 as an example (Figure 63), it is possible to describe the procedures developed to transform the shape grammar syntactic structure into an equivalent parametric design schema. In the following description, upper-case letters followed by a number

[27] 'Workbench' is the definition of different modules in CATIA. "A workbench is defined as a specific environment consisting of a set of tools, which allow the user to perform specific design tasks in a particular area (Tickoo, 2005, p. xv)."

identify points. Lower-case letters describe segments and emphasised words indicate parameters.

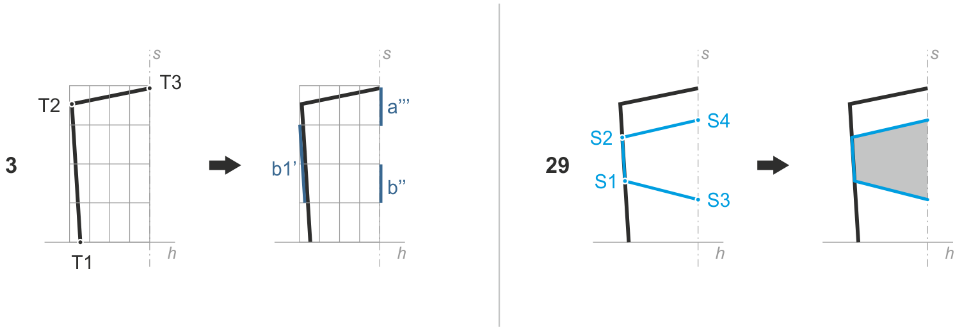


Figure 63. Rules 3 and 29 from the shape grammar

Rule 3 specifies the position of the labels that determine the parametric variation space for points. Rule 29 shows the topological relationship between profiles and differences in material application. The outer frame is defined by three points that connect two segments. T1 is coincident with the horizontal segment *h* that indicates the seat frame position. T2 defines the backrest maximum width and T3 specifies the backrest maximum height. The inner frame consists of three connected segments with four control points. Points S1 and S2 are coincident with the outer frame, and S3 and S4 are coincident with the symmetry axis. According to Rule 3, S1 and S2 can be positioned on the labelled segment b1', S4 on a''', and S3 on b''. The lengths of these labelled segments are a function of the backrest maximum height (T3 height.)

These relations must be encoded into the parametric modelling environment taking the dimensional properties of the chair components into account. Therefore, T1 width is a function of the backrest total width and T2 height a function of the backrest total height.

The complete description of this interconnected system of relations is expressed in the Cartesian space as:

T1 *(x,y)* = (seat frame height, percentage of backrest width)

T2 *(x,y)* = (backrest width, percentage of backrest height)

T3 *(x,y)* = (symmetry axis, backrest height)

b1' length = 1/2 backrest height. Positioned from 1/4 backrest height. Offset from outer frame = radius outer frame + radius inner frame

a''' = 1/4 backrest height.

b'' = 1/4 backrest height. Positioned from 1/4 backrest height.

S points positions are percentages of labelled segments.

According to these relations, there are different levels of dependency among the parameters. Seat frame height, backrest width and backrest height are independent parameters and guide the overall configuration schema. The labelled segments b1', a''' and b'' are direct dependent parameters. S points are child parameters of labelled segments. These relations enable shape grammar schemas to be translated into parametric design models, as illustrated in Figure 64.

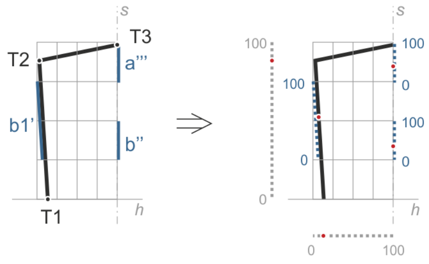


Figure 64. From shape grammar schema (left) to parametric design schema (right)

5.3.3. General Implementation Procedures

Implementation follows the parametric design schema defined in the previous step. The rectilinear wireframe model guides curvilinear representation, serving as a rig (Figure 65). The final curvilinear representation is defined by a system of interconnected geometrical elements.

Curvilinear representation takes additional features into account not described by the shape grammar, but associated with the general morphology of Thonet chairs. Lateral curvature in the back-rear leg unit, the seat frame, and the front legs are represented in the parametric design models. The implementation in this experiment encodes the round seat frame employed in the original Thonet chairs and, for the purposes of simplification, tapered front legs reflecting the contemporary redesign of Thonet chairs.

The following implementation procedures are explained by describing each chair component. Points are labelled in upper-case letters, followed by a number. The symbols ' and s express instances of projection and symmetry, respectively. Segments follow the nomenclature defined in the shape grammar. Emphasised words identify parameters and encoded equations.

The shape grammar interpretation is set on a vertical plane, according to the relations described in the previous subsection and full representation is achieved through symmetry (Figure 66). With the exception of T1, points from this schema are projected onto parameterised planes in order to define control points to generate NURBS and control additional chair components.

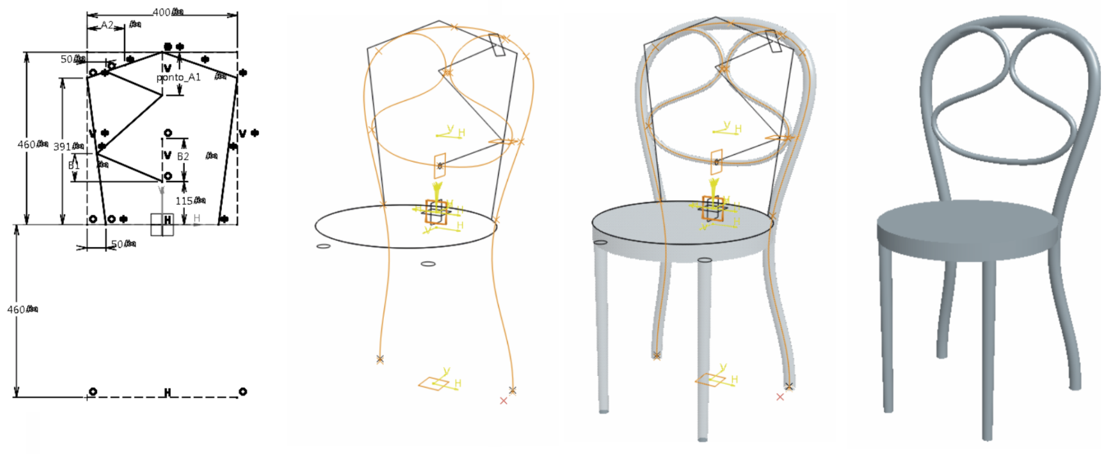
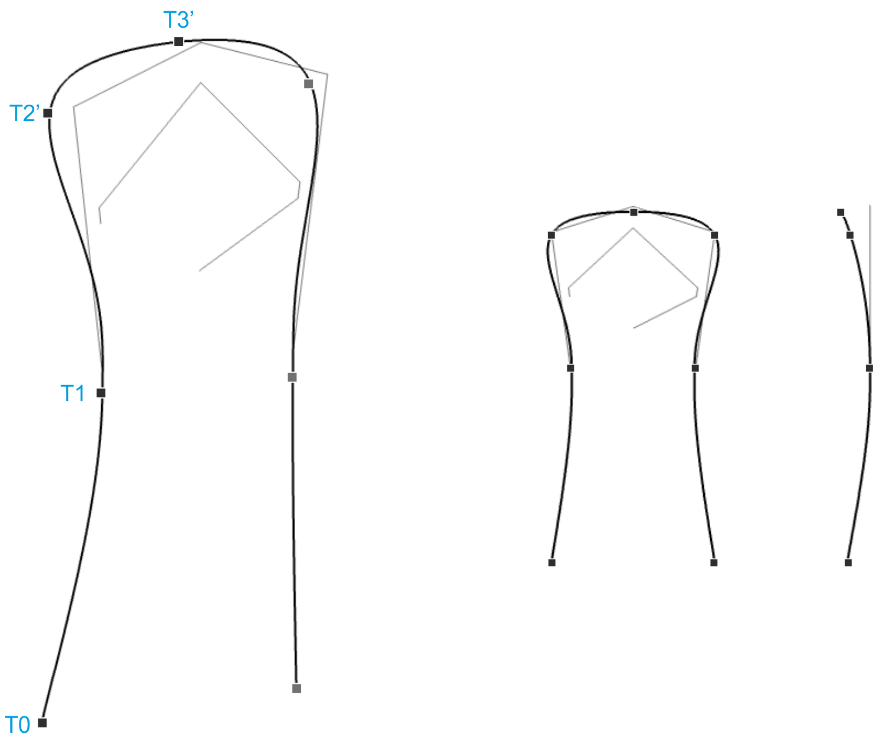


Figure 65. Internal structure of the parametric design models: rectilinear wireframe model linked to curvilinear representation.



POINTS	TANGENT DIRECTION	TENSION	PROJECTED
T0	Z-axis	0,1	No
T1	Z-axis	1	No
T2'	———	——	Yes
T3'	———	——	Yes

Figure 66. Outer frame NURBS definition

T3 is projected onto the backrest angle plane. T2 is projected towards an intermediate plane, expressed as backrest angle / 1.25. The leg indication point (T0) is projected onto the leg angle plane. These points and their respective symmetrical counterparts become the control points for a NURBS. This NURBS is the guide curve for the surface definition of the outer frame. Thonet aesthetic compliance in the NURBS is achieved through tangencies to the Z axis at T0, T1 and their respective symmetrical counterparts.

The section of the profile is a circle. Its centre is constrained to T0 and its diameter is parameterised as the OF_diameter (outer frame diameter.) A sweep between the profile section and the NURBS defines the representation of the outer frame.

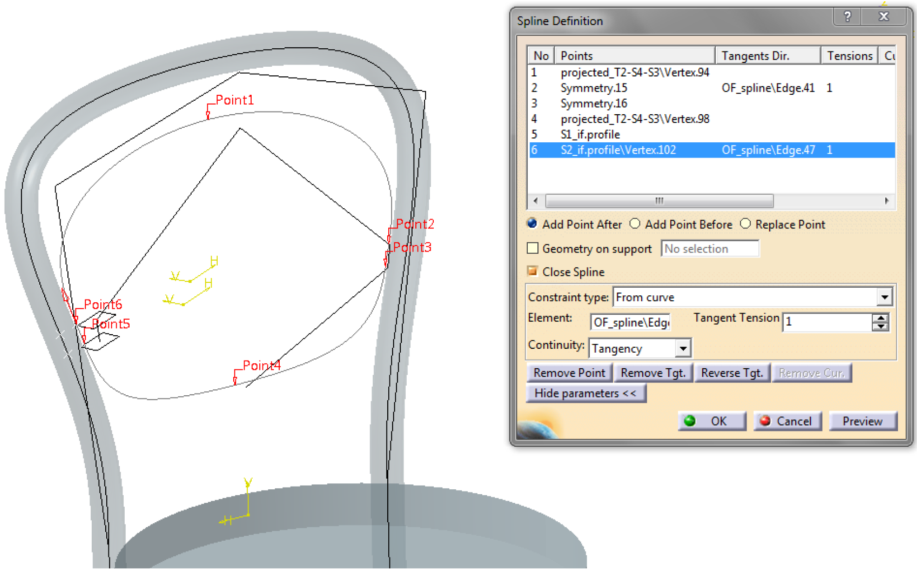


Figure 67. Inner frame NURBS definition

The interpreted shape grammar schema also controls the configuration of the inner frame. Instances of S3 and S4 are projected onto the intermediate plane. S1 and S2 instances are defined according to a procedure that requires auxiliary geometrical elements to establish conformance with the outer frame. An auxiliary horizontal plane passing through point S1 intersects the outer frame NURBS. A line connecting the intersection point to S1 constitutes the geometrical space for S1'. The distance of S1' from the intersection point is expressed as S1' = OF_diameter / 2 + IF_diameter / 2. This equation expresses the adjacency between the inner and the outer frame.

These points allow for the NURBS definition, which becomes the guiding curve that generates the surface representation of the inner frame. The NURBS for inner frame is tangent to the one that guides the outer frame, in order to guarantee aesthetic curvature conformity between components (Figure 67).

The seat frame is an extruded circle positioned on a horizontal plane. The height of the plane is an independent parameter SF_height (seat frame height.) The intersection between the horizontal plane and the symmetry plane is the placement for the centre of the circle, with a parameterised diameter SF_diameter (seat frame diameter.) This circle relates to the outer frame. The relationship is set according to the distance between the circle and both T1 and T1s, expressed as OF_diameter / 3. The extrusion value is also an independent parameter SF_thickness (seat frame thickness.)

The front legs are extruded and tapered geometrical elements, positioned on the bottom surface of the seat frame. Their definition comprises symmetrical circles tangent to the seat frame profile. The centre of each circle is a parameterised distance from the symmetry plane defined according to the equation SF_diameter / 2 x 0.65. This distance expresses the proportions observed in the analysis of the original Thonet chairs.

5.3.3.1. Specific Implementation Procedures

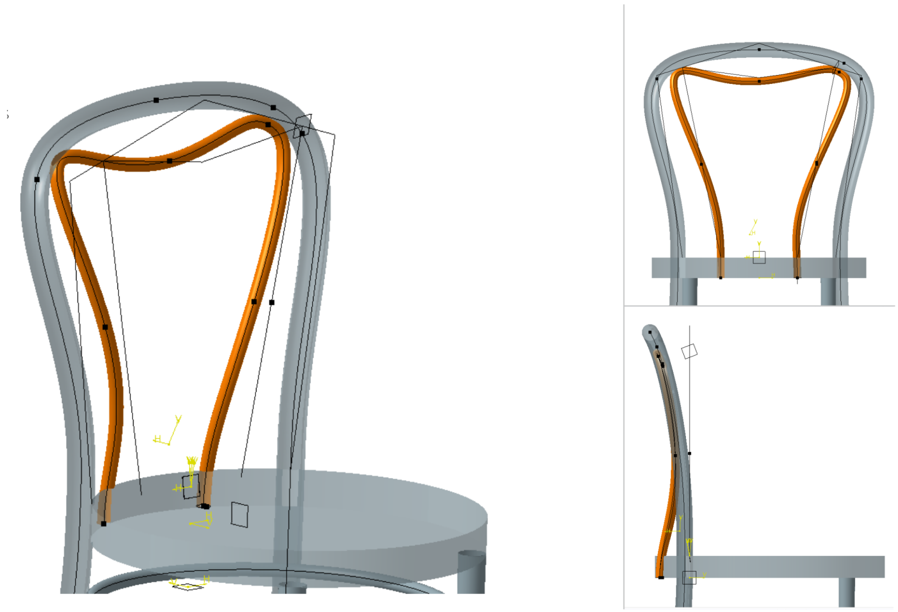


Figure 68. Inner frame connected to the seat frame

Elements in the remaining families are encoded in a similar fashion. The only difference occurs in the family in which the inner frame is connected to the seat frame and the outer frame. In this family, the inner frame definition includes further description to obtain a proper backrest curvature. A midpoint on segment P1-P2 is projected onto the backrest angle / 1.25 plane. The projected point and its symmetrical counterpart become the control points for the NURBS that guides the surface of the inner frame (Figure 68).

5.3.3.2. Generation of Customised Variants

The geometric and algorithmic relations set in the model are guided by a system of dependent and independent parameters. Three sets of parameters control the reconfiguration procedure and are directly related to the seat frame (SF), the outer frame (OF), and the inner frame (IF). Table 5 shows these categories in different colours and shades. The control parameters are exported to an Excel spreadsheet, using the CATIA 'design table' feature.

Chairs are customised by assigning values to the parameters column, therefore designing a customised variant. The complete procedure for defining a customised variant of a Thonet chair includes the following steps: (1) selection of a parametric design model and the corresponding Excel spreadsheet; (2) assignment of values to the parameters in the spreadsheet; (3) updating the CAD model with the selected customised variant. Figure 69 shows custom Thonet chairs generated using the parametric design model previously described in the general implementation procedures.

	A	B	C	D	E	F	G	H	I
1	SF_height (mm)	460	460	460	460	460	460	500	500
2	SF_diameter (mm)	420	420	460	420	450	430	450	450
3	SF_thickness (mm)	40	40	40	40	45	45	35	35
4	OF_diameter (mm)	30	30	35	30	40	35	40	35
5	OF_width (mm)	400	400	400	400	400	400	450	450
6	OF_rt_back_width_T1	25	20	25	25	20	20	30	30
7	OF_back_height (mm)	420	420	420	420	420	600	500	500
8	OF_rt_back_height_T2	85	70	85	85	85	65	65	65
9	OF_back_angle (deg)	10	10	10	10	10	5	7	15
10	OF_rear_leg_angle (deg)	7	7	7	7	7	7	10	10
11	IF_diameter (mm)	15	15	15	15	30	30	30	30
12	IF_rt_S1	45	45	65	60	45	45	40	20
13	IF_rt_S2	55	50	85	90	55	70	60	50
14	IF_rt_S3	15	10	70	35	25	10	25	0
15	IF_rt_S4	50	80	50	80	50	50	50	50
16									
17	variant	1	2	3	4	5	6	7	8

Table 5. Design table

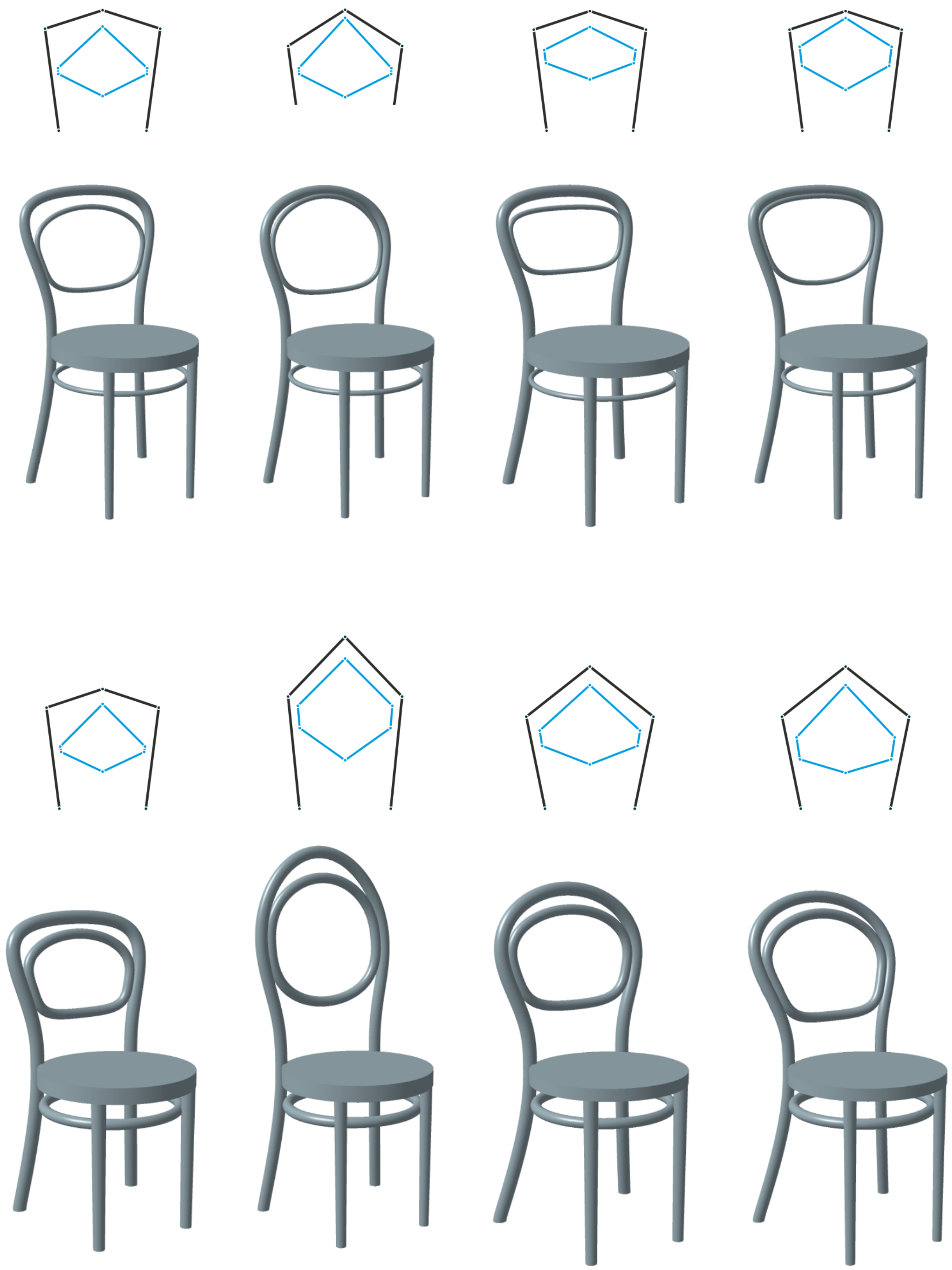


Figure 69. Customised variants generated by the same parametric design model

5.3.4. Rapid Prototyping

According to Sass and Oxman (2006), rapid prototyping can be used as part of the creative process with the aim of materializing, refining, and evaluating design ideas.

In the context of this research, rapid prototyping is used to produce physical models directly from the digital output of the parametric design models, thereby providing a tangible representation of the outcome. Since the additive process produces monolithic pieces, the tectonic study of components and their bending process are excluded from the analysis. The information obtained from this experiment enabled the parametric design models to be revised and fine-tuned.

The specific technique used to produce the 1/8 scale models was 3D Print by ZCorp. The production of scale models implied minor revisions to the parametric design models. In particular, topological tangencies were transformed into intersections to produce the monolithic component. In addition, the models were scaled and then exported to STL files to be read in the proprietary machine software (Figure 70-1). This software transforms the solid model into horizontal layers which are post-processed in the 3D printer.

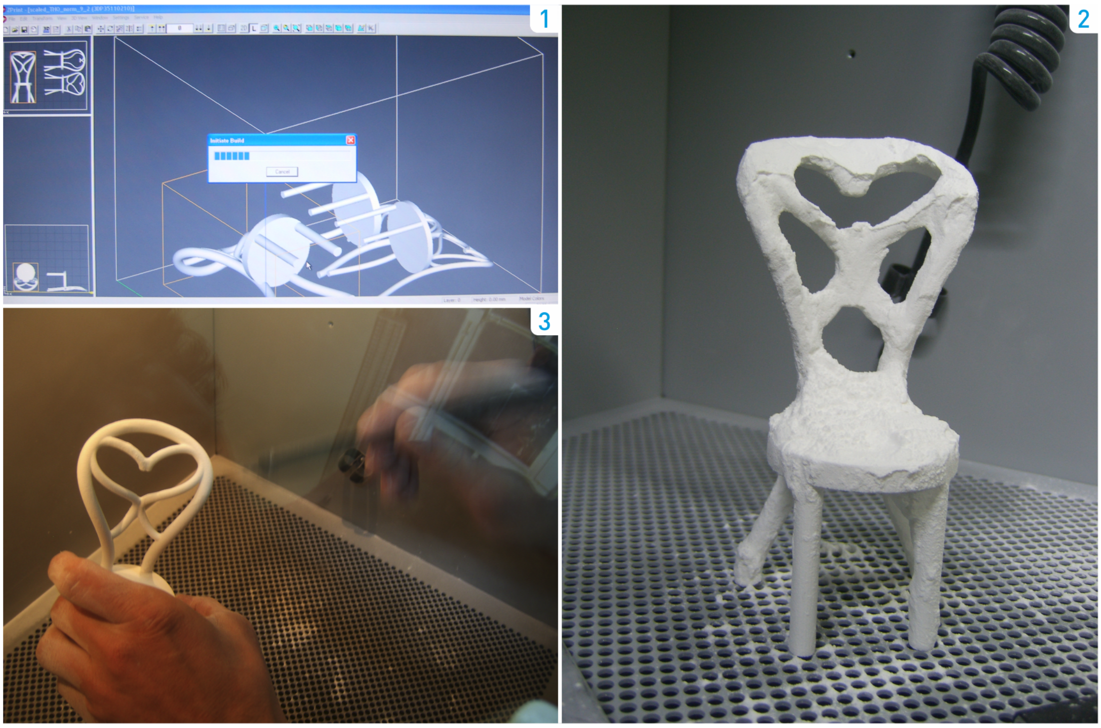


Figure 70. Steps in 3D printing

Physical model making allows for a tangible relationship between the designer and the object, even when it is computer-mediated. The method allowed for the testing of the customisation steps by generating multiple customised variants, a review of the geometric representation of the chairs and the testing of the digital fabrication process from CAD to CAM. The results provided useful information for refining the parametric design models[28].

The procedure of generating multiple customised variants enabled the usability of the parameters to be tested. The number of parameters included in the design table, on average fifteen, seems relatively high to be handled by an end-user. Although such a large number

[28] The implementation described in the previous subsections refers to refined models after assessment of the rapid prototyped models.

allows for better control over the design geometry from a detailing perspective, in terms of customisation the procedure should be simpler or more interactive. The design table does not provide the best interaction experience, since the parameter changes are not updated in real time.

Since this research focuses on the backend operations of the generative design system, the strategy followed for encoding the parametric design models favoured shape control over usability.

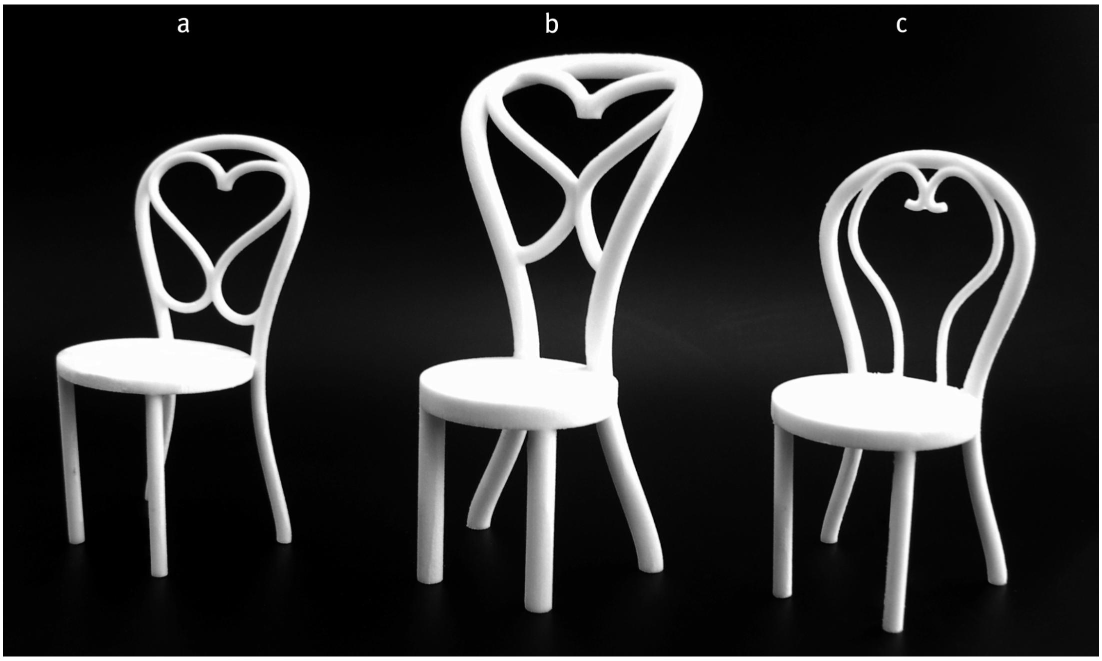


Figure 71. Rapid prototyped models of customised variants generated by two parametric design models

The generation of multiple customised variants facilitated the understanding of geometrical inconsistencies resulting from the combination of certain variables. This issue was related to the degree of freedom of constraints, which led to the refinement of the equations to allow for further design exploration. The generation of multiple customised variants also enabled the limits of the formal language to be assessed by generating chairs with proportions that extended beyond Thonet's design style (e.g. Chair b in Figure 71, with the proportions of a Mackintosh chair and a profile with a cross section too thick to be bendable with beech wood.)

The above-mentioned conditions led to a better mapping of the design space generated by the parametric design models, which was shown to be greater than Thonet's original design style. In addition, it allowed for refinement of the models.

Following aesthetic considerations, the parametric relations in the projection planes that generated the final position of the top point T3 of the backrest were refined to improve the definition of the outer frame curvature. In addition, the definition of tangency between T0 and the Z-axis was improved to obtain a more elegant type of curvature.

Comparison of the rapid prototyping models allowed conditions related to language definition to be assessed, such as the backrest maximum height, the level of distortion of inner frames across different customised variants, and the minimum distance between the outer frame profiles and their connection with the seat frame.

In future applications of the generative design system for the mass customisation of Thonet chairs, rapid prototyping can be used as a means of conveying designs to future users before proceeding to real-size manufacturing.

5.3.5. Discussion

Shape grammars and parametric design models define the subsystem of shape generation. The methods described in this section allow tacit and explicit knowledge to be encoded into a digital representation.

In the theoretical model presented here, the parametric design models are developed from previous information. Thonet's tacit knowledge and the Thonet shape grammar properties constitute the input information, which is rationalised into parametric design and encoded by parametric modelling.

The shape grammar operates on a higher level of abstraction and determines the compositional principles of the designs, based on functional behaviour. In addition to the algebra W for material selection and the space for topological variation, the points where the inner frame is adjacent to the outer frame indicate the position of screws. However, to complete the information required for encoding the parametric design models, a standard Thonet chair must be analysed. The analysis provides the complete geometrical information on the chair components, including relations between components not described by the grammar. These observations support the need for additional representations to guide the parametric design models. This premise is confirmed by other authors, namely Kilian (2006, p. 299) and Hudson (2010, p. 243), who claim that different types of representation provide better guidance through the design process with parametric models, by representing cross-dependencies between concepts and variables. In this thesis the shape grammar is used as the generative mechanism. This facilitates the implementation of parametric design models, since they provide the conceptual schema to enable the generation of multiple solutions.

The procedure of encoding grammar solutions relied on their conversion into parametric design, followed by their implementation in existing CAD software. The technique employed in the experiments is largely derived from shape grammar properties, in particular rectilinear representation. The wireframe model set on the vertical plane was a straightforward conversion of the rationale of shape grammars. Following this, sets of auxiliary geometrical constraints – planes, intersections, projections, tangents and symmetries – define the final position of key elements of the wireframe model. These elements then become control entities for surface definition. The system of interconnected relations between these elements enables the rectilinear representation to be translated into a curvilinear one.

There are advantages in the use of this technique. Considering Woodburry's (2010, p. 22) distinction between geometric construction and programming techniques in parametric design, the technique described here relies on geometric construction. The geometrical reconfiguration procedure is guided by mathematical equations. The set of skills needed to implement this type of parametric model therefore remain the work of a trained product designer. Another advantage is that most of the equations directly related to shape grammars are set in a single CATIA sketch. This modular approach reduces the complexity of the model and makes its structure explicit. It proved effective in the parameterisation procedures, when there was a need to test different combinations of equations in order to fine-tune relationships between elements.

The three main design families encoded into the shape grammar were translated into five parametric design models. An average of thirty-five equations explained the relations between the geometric elements in each parametric design model. The generic customisation procedure for the chair structure is defined by eleven explicit parameters in the design table. The customisation of the inner frame is defined by three to five additional parameters.

The time-consuming task of developing the parametric design models can be considered a disadvantage in comparison to traditional digital modelling techniques. In fact, it requires additional testing to set the solution space, understand parameter interrelationships and anticipate possible errors. Nevertheless, the procedure leads to a closer relationship between both the details and the effects on the shape of the product. This type of predictive thinking evaluates the extent of possible solutions (Kilian, 2006, p. 110).

The testing of the subsystem part and the rapid prototyping of its output provided information for refining the language. However, the goal of the generative design system is to establish information for the production of custom chairs. Therefore, the system must include a shape evaluation subsystem in order to guarantee that the custom chairs generated by this part comply with the structural requirements for production.

Customisation requires a different design description to conventional design processes. Instead of establishing the design intent then proceeding to the detailing for fabrication, shape customisation requires a description of the design possibilities with a degree of freedom that enables the final design solution to be tailored according to specific design context considerations. The shape generation subsystem models the design space on the basis of this principle. The parametric design models in particular allow for both shape customisation and connection to the latter steps of the design process.

The following two sections present the shape evaluation subsystem, which uses the parametric design models as input information.

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5.4. Simulation

This section describes the simulation, which is the first part of the shape evaluation subsystem. It is presented through a description of the implementation procedures, analysis of the results and a discussion of the simulation in terms of the general goals of the generative design system.

5.4.1. Introduction

The output of the generative design system provides information suitable for the production system, leading to the construction of the physical chair. Accordingly, each customised variant becomes a final product rather than a prototype. This intrinsic principle determines the need to include a shape evaluation subsystem within the generative design system. This analytical subsystem aims to ensure that the structural mechanics of the chairs generated in the previous steps in the design process comply with legal performance standards. In addition, the interpretation of results leads to a better understanding of the influence of particular parameters on the behaviour of the whole structure. In theory, this type of information may determine a refinement of the language, by limiting the parametric design models to ensure that only chairs that meet the required structural standards are generated.

The ISO standards for testing domestic chairs (ISO, 1989) deal with issues such as strength, durability and safety requirements and these are directly associated with material properties and structural integrity. These issues can be virtually tested through computer-aided engineering (CAE) using the Finite Element Method (FEM) (Adams & Askenazi, 1999). FEM is able to simulate the performance of designs based on the calculation of a discrete digital model.

5.4.2. Simulation Setup

FEM tests are conducted using the CATIA 'Generative Structural Analysis' (GSA) workbench, which is a CAE environment for simulations. Since both the generation of designs and the FEM analysis use the same software, the same geometric data can also be used. The setup of the analysis model must be prepared in both the CAD and CAE environments in order to recreate the ISO test conditions.

The data pre-processing starts with the parametric design models and involves representing the loading pads and attributing the material properties. The ISO apparatuses are constrained to the respective chair areas. The beech wood chair structure is defined with the following material properties: a Young modulus of 15 GPa and a mass density of 737 kg/m^3.

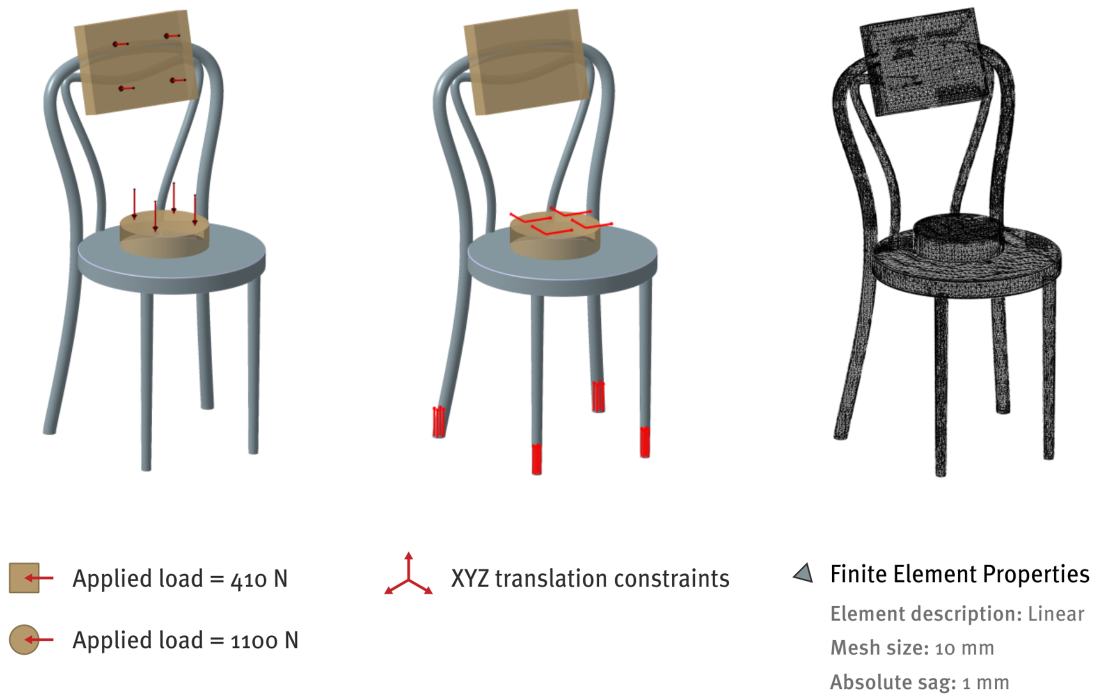

Figure 72. Key steps in the FEM model setup for structural analysis

In the CAE environment the model is completed with information on applied loads, translation constraints and finite element properties (Figure 72). The forces applied perpendicularly to the loading pads follow ISO requirements. Movement constraints aim to simulate the performance of a stable chair resting on a horizontal surface. The simulation model comprises a tetrahedral discrete mesh whose elements have a maximum edge dimension of 10 mm. The maximal gap between the mesh and the geometry is 1 mm.

The results are analysed using the Von Mises yield criterion. Further examination consists of the analysis of nodal displacements. Wood is an anisotropic material, but can be analysed as an orthotropic material in numerical simulations (Mackerle, 2005, p. 580). In order to increase the reliability of the results, the Eurocode 5 standardised criterion is used. It takes into account the "uncertainty in the resistance model used for design together with the adverse effects of geometric deviations in addition to the effect of unfavourable deviation of material or product property" (Porteous & Kermani, 2007, p. 66).

The criterion is expressed as:

$$R_d = k_{mod} \frac{R_k}{\gamma M}$$

in which k_{mod} (0,6) is a modification factor that takes into account the effect of load duration, γM (1,3) is a factor for material property and resistance in the ultimate limit state, and R_k (46 MPa) is the standard value for the compressive yield strength of beech parallel to grain (Matweb, 2011). The R_k value considers the bending procedure used for the wooden rods, which follows the direction of the grain, meaning that when the chair is in use the stress is applied in this direction. The calculated modulus of rupture (R_d) used to appraise the simulation results is 21.2 MPa.

5.4.3. Experiments

The aim of the initial verification is to study the effect of varying the outer frame diameter, the backrest height, the seat frame thickness, the backrest angle and the rear leg angle.

These considerations led to the establishment of several configurations for testing, which can be categorised into two groups (Table 6). The proportions of a standard Thonet chair defines group A, configured with a backrest height of 420 mm. In the group B the backrest height is 80 mm higher. Each group comprises six variants for testing the outer frame diameter (25, 27, 29, 31, 33 and 35 mm), which leads to the first set of tests. In the second set of tests the value of the seat frame thickness is 60 mm. The third and fourth sets of tests vary the value of the backrest angle to 0º and 20º, respectively. The fifth set of tests vary the value of the rear leg angle to 12º.

5.4.3.1. Analysis of Results

The computed solutions confirm the empirical knowledge that the maximum amount of stress occurs in the connection area between the outer frame and the seat frame (Figure 73). Likewise, displacement is greater across configurations in the group B, which displays higher backrests.

In the sixty tests described above, the results showed that stress and displacement do not increase in a linear progression. According to the results shown in Table 6, considering a 15% security margin from the modulus of rupture (18 MPa), few variants meet these requirements. In the group A, the success rate is higher than in the group B. Variants categorised under group A complied in nineteen out of the thirty tests, whereas variants categorised under group B complied in four out of the thirty tests. The four variants in group B comprised a 20º backrest angle.

Apart from the outer frame diameter, the results show that a greater backrest angle and rear leg angle reduce the stress in the outer frame.

	Parameters	A: backrest height = 420mm						B: backrest height = 500mm					
p1	SF_height (mm)	460	460	460	460	460	460	460	460	460	460	460	460
p2	SF_diameter (mm)	420	420	420	420	420	420	420	420	420	420	420	420
p3	SF_thickness (mm)	40	40	40	40	40	40	40	40	40	40	40	40
p4	OF_diameter (mm)	25	27	29	31	33	35	25	27	29	31	33	35
p5	OF_width (mm)	400	400	400	400	400	400	400	400	400	400	400	400
p6	OF_rt_back_width_T1	25	25	25	25	25	25	25	25	25	25	25	25
p7	OF_back_height (mm)	420	420	420	420	420	420	500	500	500	500	500	500
p8	OF_rt_back_height_T2	85	85	85	85	85	85	85	85	85	85	85	85
p9	OF_back_angle (deg)	10	10	10	10	10	10	10	10	10	10	10	10
p10	OF_rear_leg_angle (deg)	7	7	7	7	7	7	7	7	7	7	7	7
p11	IF_diameter (mm)	20	20	20	20	20	20	20	20	20	20	20	20
p12	IF_rt_P1	0	0	0	0	0	0	0	0	0	0	0	0
p13	IF_rt_P2	50	50	50	50	50	50	50	50	50	50	50	50
p14	IF_rt_P3	50	50	50	50	50	50	50	50	50	50	50	50
1	Von Mises stress (MPa)	20,4	23,5	18,6	15	15,5	17	39,3	26,1	22	20,7	20,4	19
	Structural displacement (mm)	8,4	7,22	5,99	5,09	4,31	3,69	12,1	10,6	9,14	7,82	6,74	5,97
p3	SF_thickness (mm)	60											
2	Von Mises stress (MPa)	20,9	23,3	19,1	16,2	14,4	14,6	40,8	29,7	27,6	24,1	21,1	18,6
	Structural displacement (mm)	8,41	7,16	6,03	5,05	4,27	3,66	12,3	10,6	9,18	7,93	6,84	5,94
p9	OF_back_angle (deg) *	0											
3	Von Mises stress (MPa)	26	20,7	19,3	22,5	15,6	15	29,3	28,5	22,7	23,1	21,1	21,4
	Structural displacement (mm)	10,3	8,58	7,22	6,06	5,04	4,29	17,8	14,1	12,4	10,2	8,7	7,35
p9	OF_back_angle (deg) *	20											
4	Von Mises stress (MPa)	18	17,3	15,2	13,1	12,9	16,9	22	17,7	20,7	17,6	16,1	12,8
	Structural displacement (mm)	5,61	4,96	4,39	3,86	3,45	3,01	7,79	6,96	6,22	5,03	4,52	3,99
p10	OF_rear_leg_angle (deg) * **	12											
5	Von Mises stress (MPa)	24,5	17,2	17	16	16,2	13,8	24,3	31,2	21,9	28,8	20	19,1
	Structural displacement (mm)	8,69	7,28	6,28	5,38	4,6	4	12,7	11	9,48	8,08	7,13	6,07

* SF_thickness (mm) = 40

** OF_back_angle (deg) = 10

- MPa value within the 15% security margin (18 MPa)
- MPa value above the 15% security margin (18 MPa)

☐ Parameter value changed

Table 6. Results from simulation tests

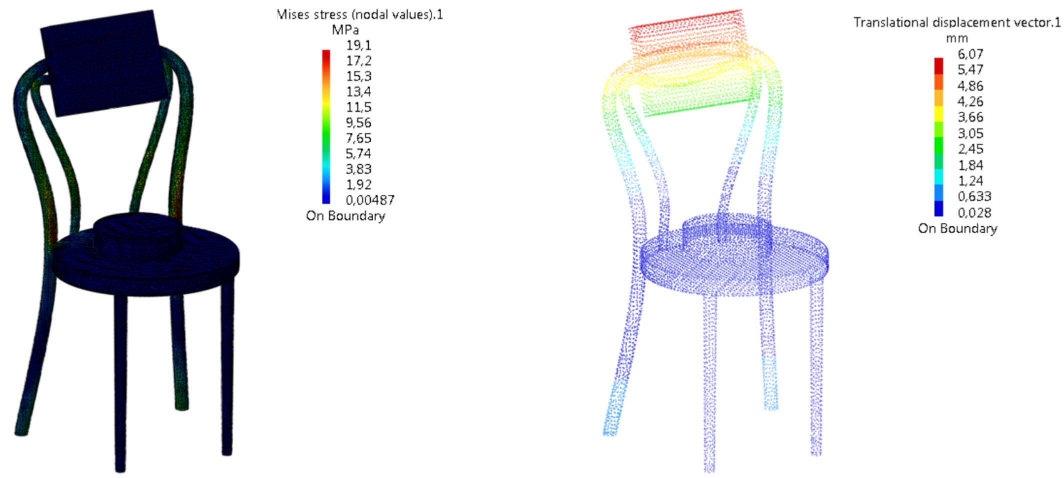

Figure 73. FEM analysis: Von Mises stress and structure displacement

5.4.4. Discussion

The simulation presented considers the usability of integrative computer-aided design and engineering tools as a fundamental requirement for the proposed generative design system. FEM permits structural behaviour to be assessed before construction, which leads to agile product development. This is a very important subject given the possibility of custom designs that may be unique.

In terms of the flow of information developed in the previous steps of the design process, FEM tests allowed for a more accurate perception of the effect of certain parameters on the overall mechanical behaviour of the chair as a load-bearing structure. However, there are certain limitations which can be characterised under three headings: reliability of information; reuse of the analytical models; support for refining a generated custom chair.

FEM offers an approximate solution to the problem. The considerations used to encode the mesh definition and analyse results follow the recommendations in the literature for the most unfavourable conditions. Nevertheless, the results must be confirmed by verifying them against the equivalent outcomes from real physical testing. Since the manufacture of custom chairs is beyond the scope of this research, the absolute correctness of the simulation model cannot be ensured. In future work, real testing will provide the capacity to validate results or fine-tune the encoded digital information.

The use of integrative software with different workbenches to support the generation and simulation steps of the design process facilitated information links between parametric design models and simulation models. Maintaining parametric relations reduced the time required to reconfigure the models to test new configurations. If different software was used to perform each step of the design process, it would be necessary to configure a customised variant, export it to a neutral exchange file, import it to FEM software, set up the model and then perform the analysis. These procedures would need to be repeated for each test, thereby making the task more time-consuming.

Although there was interoperability between workbenches, refinement *per se* is a time-consuming procedure. Whenever a customised variant failed to meet structural requirements, the parameters had to be manually adjusted in the parametric design model. Since there is no parametric update of the features defined in the GSA workbench, any variation in the backrest angle involved a manual update of the load before running the intended new test.

FEM analysis is limited due to the unidirectional flow of information. This condition, observed after analysis of these experiments, had already been noted by Kilian (2006, p. 55–56):

“The core limitation of FEM methods for design exploration is their one-directional, analytical nature. The result of a FEM analysis (...) offers little in terms of how to change the geometry to overcome any problems detected in the analysis. This makes the approach of little use for an exploration based design approach, unless it is combined with an optimization technique that runs through a large number of design iterations using a fitness function to measure the progress.”

Bilateral integration between parametric models and FEM models has already been researched. The lack of commercial software with these capabilities determines the need for computer programming to develop custom solutions. Guajarati and Ma (2011) proposed the common data model (CDM), which is a neutral model that stores the information generated in different software packages, such as parameters, parametric relations, material properties, load information, mesh definition and other data created during the design process. CDM acts as an information repository that allows the user to manipulate the generative mechanism and guarantees interactive updates across different modules. The design system encompasses design specifications produced on conceptual and detailed levels. Moreover, it records design revision cycles, providing the ability to change and compare design iterations. The centralised model and decoupling of complexity on two levels provides for the bilateral integration of parametric and CAE models.

The results from the sixty experiments described above focused on a narrow interaction between parameters. Given the possibility of combining parameters, there is a large domain of possible solutions. Intuitive and manual testing of this possibility in order to reach a better understanding of the solution domain is not suitable for the goals of the design activity envisaged. In order to resolve these issues, the optimisation part was formulated, which integrates performance information as the driver of automatic design reconfiguration. The following section presents optimisation as a complementary method to overcome FEM limitations, and its modelling as a part of the shape evaluation subsystem.

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5.5. Optimisation

5.5.1. Introduction

The FEM analysis results demonstrated that a narrow parameter variation determines how well a customised variant performs structurally. Given the large domain of possible solutions, optimisation was therefore formulated to overcome this limitation, providing an automated search within a set of predefined conditions. Optimisation is a conditional part of the generative design system that acts on information generated in both the parametric design models and the simulation models.

Optimisation follows the principles of the proposed generative design system, in which the computer is used to assist the designer in the creation of algorithmic driven designs. The boundary conditions for the optimisation problem are both aesthetic and functional, thus reflecting the need for designs in the Thonet design language to perform according to ISO standards.

In order to optimise a design it is necessary to formulate a problem in mathematical terms with different constraints that can be measured and satisfy performance criteria expressed as objective functions (Arora, 2004). The search for optimum designs is then achieved through a simulation using optimisation algorithms.

In this case study a simulated annealing algorithm is used for sizing and shape optimisation problems. Since the shape grammar solutions are encoded into the equivalent parametric design models, there is no generation by rule application nor shape emergence. The algorithm must handle parameter constraints in order to optimise their size and shape to meet predefined specifications. This is accomplished by using the available computational optimisation techniques embedded in CATIA. The existence of a graphic user interface provided a shorter learning curve for the pre-processing and post-processing of data, whilst meeting the initial goals for design automation to assist the search in a large solution space.

This section presents the general implementation procedures for two problem formulations: minimisation of equivalent stress and minimisation to a target value. The first problem formulation assesses the suitability of the algorithm for the goals of the generative design system. The second problem formulation features an application for a real design problem in the domain of customisation procedures. The results are analysed in terms of the goals of the generative design system. The section ends with a discussion on the use of optimisation tools in the generative design system.

5.5.2. General Implementation Procedures

The custom Thonet chairs were optimised using the CATIA 'Product Engineering Optimizer' (PEO) workbench. This workbench provides a set of tools that allow the user to define an objective function and select the design variables to be optimised. The objective function can be searched to a minimum, maximum, or target value. The optimisation requires information defined in previous steps of the design process, such as geometric parameters from the parametric design models and results from the simulation. The solution space for the search is established by the selection of CAD parameters and their variation range.

A given design is optimised according to both user specifications and the selection of different built-in algorithms. During the optimisation run the algorithm generates several iterations of chair configurations. Each iteration displays different combinations of variables in order to find a solution to the formulated problem. The parameter values representing the different generated iterations are listed in an *.xls file, thereby providing the possibility of reusing optimisation information.

The following experiments use a simulated annealing algorithm for the stochastic optimisation of customised variants.

5.5.2.1. Problem Formulation

As previously stated, two problems were formulated for the optimisation experiments: (1) minimisation of maximum equivalent stress and (2) minimisation to a target value of 18 MPa, which corresponds to a safety factor of 15% below the resistance limit. The respective objective functions can be expressed as:

1) $\min(\max(\sigma_{\text{eq i}}))$

2) $\max(\sigma_{\text{eq i}}) \sim 18\text{MPa}$

The variables subjected to optimisation were dimensional parameters selected from the parametric design model. Their domain was constrained to a range of integer values, thus setting a discrete optimisation problem. The definition of the range for the optimisation complies with the design principles observed in the original Thonet design style (Table 7; Figure 74). In the definition of lower bound of the design space, the values for the seat frame height and diameter, and for the outer frame backrest height, angle and rear leg angle are the lower values found in the analysis of Thonet chairs. The values for the outer frame diameter, the inner frame diameter and the seat frame thickness were equally extracted from the analysis of Thonet chairs, and lowered by 10%, 15% and 50%, respectively. A customised variant that uses the values corresponding to the lower bound does not meet the structural requirements. It has the proportions of a standard Thonet chair, but thinner beech profiles are employed in the outer frame, the inner frame and the seat frame. The upper bound of the design space is defined according to the dimensions observed in a larger Thonet armchair featured in the 1904

Catalogue (Thonet Company, 1980). The outer frame diameter has a thicker bendable beech wood profile and the variation of its backrest angle is set according to seating considerations specified in anthropometric literature (Diffrient et al., 1985).

The customised variant using variables values corresponding to the lower bounds was submitted to the two sets of tests. The compressive yield strength parallel to grain for this initial variant was calculated as 39.4 MPa, 84% above the yield limit. This approach of using the lower bound values, rather than using random or feasible values, was employed to test the algorithm's capacity to search the entire space of solutions.

Parameters		Lower bound	Upper bound	Increment
p1	Seat frame height	450 mm	480 mm	1 mm
p2	Seat frame diameter	420 mm	510 mm	1 mm
p3	Seat frame thickness	30 mm	60 mm	1 mm
p4	Outer frame diameter	27 mm	40 mm	1 mm
p5	Outer frame width	400 mm	510 mm	1 mm
p6	Outer frame backrest height	420 mm	530 mm	1 mm
p7	Outer frame backrest angle	8 deg	13 deg	1 deg
p8	Outer frame rear leg angle	4 deg	10 deg	1 deg
p9	Inner frame diameter	10 mm	30 mm	1 mm

Table 7. Range of parameters defining the boundaries of the design space

A simulated annealing (SA) algorithm was selected to search for optimal designs. In the PEO workbench, the SA optimisation setup provides the user with the ability to select the speed of convergence, from slow, medium, fast and infinite (hill-climbing). Conversion occurs when the algorithm reaches a solution. Termination criteria may be set as time, maximum number of iterations, or number of iterations without improvement.

Four sets of experiments were carried out, each corresponding to a type of convergence speed. In each set, four time configurations were established as termination criteria: 20, 40, 200 and 400 min. The "lower bound chair" was submitted to the optimisation experiments.

The experiments aim to provide a direct understanding of the suitability of the SA algorithm for optimising custom chairs and, more specifically, whether the aesthetics of the optimised chairs comply with the design language. In addition, the analysis and interpretation of the optimisation results should provide information on the preferred values for parameters and the combination between parameters, such as optimised ratios between outer and inner frames, or between backrest angles and backrest heights. This type of information may be used in a future refinement of the design language generated by the system.

Figure 74. Visualisation of the boundaries of the design space

5.5.3. Analysis of Results

5.5.3.1. Minimisation of Maximum Equivalent Stress

A	B	C	D	Value of Optimised Parameters									E
				p1	*p2*	*p3*	*p4*	*p5*	*p6*	*p7*	*p8*	*p9*	
Slow	20	98	25	453	431	34	39	407	458	9	7	27	75.4
	200	1175	805	453	431	34	39	407	458	9	7	30	76.0
	400	694	458	452	420	49	39	407	420	10	4	30	80.8
Medium	20	109	25	453	431	34	39	407	458	9	7	27	75.4
	200	460	25	452	420	49	40	407	421	13	4	31	79.2
	400	2081	1735	453	431	34	39	407	458	9	7	30	76.8
Fast	20	95	25	453	431	34	39	407	458	9	7	27	75.4
	200	1039	656	450	420	46	39	405	420	11	6	29	80.2
	400	2201	540	450	420	31	39	400	421	13	4	30	78.0
Infinite	20	28	23	450	420	34	39	405	420	11	8	29	79.6
	200	268	23	450	420	34	39	405	420	11	5	29	79.6
	400	538	508	450	420	34	39	405	420	11	8	31	80

A – Type of convergence speed
B – Time (minutes)
C – Number of iterations
D – Iteration of convergence
E – Percentage of stress reduction

Table 8. Optimization results for the minimisation problem

The results showed the effectiveness of the algorithm in optimising the chairs, decreasing the stress by an average of 78% (Table 8). At fast and medium convergence speed, the 200-min tests provided the best results. With slow and infinite, this was achieved in the 400-min tests.

A 400-min test with slow convergence speed yielded the best result for this problem formulation, decreasing the stress by 80.8% and converging with fewer iterations than the fast and medium tests. In all these tests, the optimisation of the outer frame diameter was the key to finding the optimal design. The algorithm set this variable close to its maximum and then continued the search by combining other variables.

This type of problem formulation was useful in assessing how different types of convergence speeds explore the range of the parameters. It also provided a better understanding of the ratio between the outer and inner frames. Initially set as 0.37 it was optimised to an average of 0.75 in all the tests. This result is close to the 0.65 proportion verified in the original Thonet design style. These observations may be useful for refining parameter relations in the parametric design models.

In fast convergence speed tests, the 20- and 40-min setup generated an optimised variant (the same in both tests) with a higher level of style compliance in comparison to those produced in the 200- and 400-min tests. The reasons are associated with chair proportion as a single unit and proportion across components. As the outer frame profiles are thicker, visual elegance is achieved by a higher backrest height and a higher seat frame height. In addition, proportion across components is closer to the original Thonet design style. The seat frame thickness is closer to the outer frame diameter and the ratio between the inner and outer frame is 0.69.

5.5.3.2. Minimisation of Maximum Equivalent Stress to 18 MPa

Since this problem formulation is not as linear as the minimisation problem, convergence with the objective function was achieved by additional iterations in the majority of tests. Moreover, the boundary of 40 mm for the outer frame diameter was not reached (Table 9). The optimised chairs bear a strong resemblance across the different tests.

In the different experiments, the level of style compliance is observable only in details relating to mathematical proportions. Following this principle, the infinite and medium convergence speeds proved best suited to meeting the initial goals of optimisation. This was accomplished by generating optimal solutions using the thinnest profiles and a ratio of 0.6 between the outer frame diameter and the inner frame diameter. The medium convergence speed tests also provided a wider search space between variables, generating chairs with a greater level of compliance with the aesthetic criteria of the Thonet design style. In the 20- and 400-min tests, the infinite option was the fastest to reach convergence, while in the 200-min test, the medium convergence speed provided the optimal solution in 17 iterations out of a total of 414.

A	B	C	D	Value of Optimised Parameters									E
				p1	*p2*	*p3*	*p4*	*p5*	*p6*	*p7*	*p8*	*p9*	
Slow	20	102	68	451	428	33	32	411	420	9	4	17	17.9
	200	417	308	461	420	39	37	400	433	8	6	10	17.9
	400	857	638	450	421	33	30	408	420	12	8	18	17.9
Medium	20	68	93	451	428	33	32	411	420	9	4	17	17.9
	200	414	17	450	421	33	30	408	420	12	8	18	17.9
	400	855	638	450	421	33	30	408	420	12	8	18	17.9
Fast	20	91	68	451	428	33	32	411	420	9	4	17	17.9
	200	1323	158	450	426	32	32	410	420	9	4	16	18.0
	400	2663	2631	450	426	32	32	410	420	9	4	16	17.9
Infinite	20	29	16	452	421	34	35	401	423	9	5	15	17.8
	200	1190	122	450	420	30	31	400	421	11	4	17	18.0
	400	2484	122	450	420	30	31	400	421	11	4	17	18.0

A – Type of convergence speed
B – Time (minutes)
C – Number of iterations
D – Iteration of convergence
E – Stress Value (MPa)

Table 9. Optimization results for the 18 MPa target problem

5.5.4. Discussion

Stochastic algorithms combine random variables, which means that it may not necessarily follow the same search paths every time is runs. The CATIA SA algorithm showed a deterministic update of iterations in some experiments. This condition is assessed by analysing experiment results with the same initial setup and different conversion speeds. A closer examination of fast convergence speed tests in the 18 MPa target problem formulation supported this idea. In this set of tests the 20-, 40-, 200- and 400-min setups provided a total of 91, 241, 1323 and 2663 iterations, respectively. In the tests as a whole, 66 iterations corresponded to the same customised variant. Comparison of the 200- and 400-min tests shows a total of 1322 equal iterations.

This means that a test with a longer time setup does not necessarily generate better results. Tests with longer optimisation runs did not improve the results. In experimenting with different time setups, the 200-min tests provided the best trade-off between exploration of the variable space and response to the formulated problems.

Despite the deterministic update of iterations in some tests, the SA algorithm proved useful in solving the optimisation problems formulated. The use of an automatic procedure to generate acceptable solutions within the range set by the design language streamlines the design process. It would not be possible for the designer to search a similar solution space or generate and evaluate the same number of alternatives in the same time.

The ability to analyse alternatives in a shorter time and retain the relevant information needed to select the best potential definitive layouts improves the performance of the design process. As results show, there is a range of optimal designs for both the problems formulated rather than a single solution (Figure 75). The results must therefore be analysed further by the designer, rather than simply accepted. This provides additional insights into the impact of each variable within the overall context of the chair as a structure. In addition, in analysing the optimisation results, the designer also reflects on the nature of the parameterisation procedure, in particular the number of explicit parameters, their range, and the hierarchy between the encoded relationships. This knowledge can be helpful in terms of relaxing parameters and modelling under-constrained sketches to support additional shape exploration.

Non-optimised chair

Optimised chair
- Minimisation Problem
- Slow convergence speed
- 400 minutes

Optimised chair
- Target 18MPa Problem
- Medium convergence speed
- 400 minutes

Figure 75. Visual comparison of non-optimised and optimised chairs

Optimisation is the dynamic counterpart of FEM analysis. FEM is a unidirectional connection from design to analysis that does not state how to solve the problems. Optimisation, on the other hand, complements the generation procedures by reconfiguring shape features according to performance results. The automatic refinement of shape properties enables the user to further explore the customised variants and find potential best solutions prior to manufacturing. This condition is very important in the context of mass customisation because it enables unique designs to be produced that are structurally viable.

The prediction of better designs depends on how the problem is formulated. The designer selects the parameters and their range and specifies the objective function and algorithm parameters. In the end, it is the designer who evaluates the optimised design, taking into account other design goals that are not expressed in the objective function. Therefore, optimisation is a technique that assists the designer but does not substitute his/her work.

In a conventional design process, creativity is tapered throughout the steps until it reaches the definitive layout that is optimised for fabrication. In the proposed generative design system, the goal is the generation of multiple feasible definitive layouts. The system therefore extends the possibility of searching for solutions to the latter step of the design process, by incorporating knowledge of physical behaviour and fabrication issues.

The specification of the parameter variation range in the optimisation formulation requires predictive thinking to estimate the definition of the solution space. This type of thinking is crucial to the definition of the design language. It is a different type of design thinking to the design of a single solution or a modular product. In the design of a single solution, the preliminary layout is evaluated and optimised to achieve a definitive layout. With modularity, the product is designed as a system with standard interfaces that accommodates multiple components. Designing a design language with shape grammars, parametric design and specifications for the optimisation range requires thinking of the preliminary layout as a 'meta-preliminary layout'. The range of topological and geometric variation specifies the solution space for this meta-preliminary layout. There is a progressive specification of the custom solution throughout the successive parts of the generative design system. The system must encompass information on the formative procedures of the design language, allow for customisation of shape properties, and ensure that the generated customised variant (preliminary layout) is feasible and structurally sound before construction (definitive layout.) The use of digital design tools facilitates the exchange and reuse of information generated in the different steps of the design process.

The use of digital design tools has progressed from the execution of final drawings towards integrative tools that support the design, analysis and manufacture of products. In a design-to-production context – in both academic and practical terms – the convergence of CAD, FEM analysis and CAM provides new opportunities for collaboration in the fields of design and engineering. Oxman and Oxman (2010, p. 15) state that the traditional sequence of "form, structure, material" can be reversed by the application of technology in the design process to become "material, structure, form".

The approach presented here follows the conventional approach of developing analytical models in the latter steps of the design process as validation techniques to support structural performance. The generative design system emulates these conditions in the digital realm. The design process for mass customisation includes the manipulation of the four parts of the system. First, a topological version, which serves as a candidate solution, is generated using the shape grammar rules. This solution is then manipulated using a topologically equivalent parametric design model, thereby generating dimensionally different customised variants. Following this, the structural behaviour of the resulting customised variants is assessed using the simulation part. Finally, the optimisation part enables the combination of parameter values in the parametric design model to be found that offer the best performance under the specified conditions.

Analysis of the optimisation experiments may constitute an additional iteration in the development of the generative design system. The knowledge provided by optimisation tools can lead to refinement or even the creation of novel design languages based on an assessment of the knowledge acquired in developing the optimisation part.

The tool used in the experiments proved suitable for the general goal of the generative design system. Nevertheless, some features limit the performance of the designer in the context of mass customisation if s/he is unable to do some scripting. In order to become a real computer-aided design synthesis tool with a potential use in future situations, it would be beneficial for it to be able to record activities and learn from previous experiments (Gero, 1996). Furthermore, it would be useful to define weighting factors for the parameters, thus establishing a search hierarchy.

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5.6. Summary of the Chapter

This chapter detailed the generative design system, which followed a decomposition of the customisation problem into four sub-problems: generation, exploration, simulation and optimisation. The decomposition into these four sub-problems permitted the modelling of each sub-problem separately, facilitating its implementation (Figure 76).

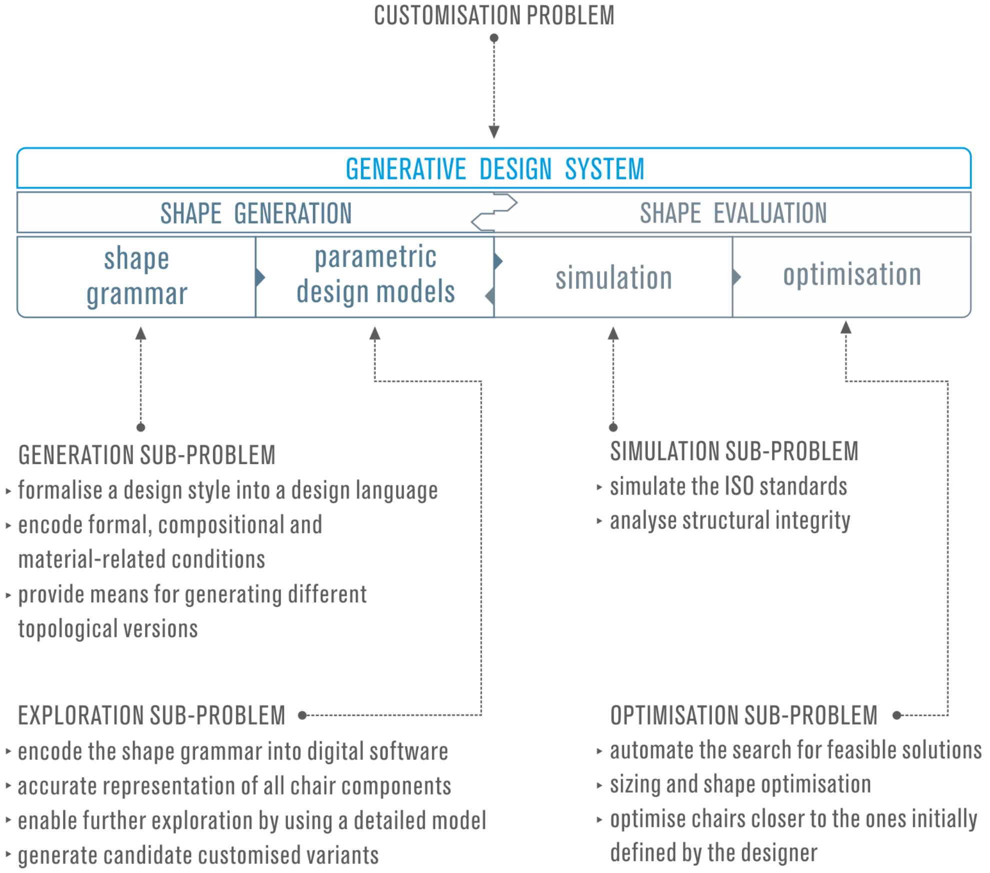

Figure 76. Decomposition of the customisation problem into sub-problems that correspond to the constituent parts of the proposed generative design system

The generation sub-problem addresses the codification of the formal, compositional and material-related conditions verified in the analysis of the design style (Section 4.4). These features were encoded into the shape grammar (Section 5.2.). The use of a higher abstraction model enabled the decomposition of the shape into its fundamental principles and simplified the encoding of the functional requirements. Functional requirements were encoded as shape grammars' labels, which enabled preliminary layouts to be generated within a constrained solution space, defined to guarantee a feasible arrangement of elements. Labels act as an implicit device to constrain the solution space, rather than an explicit evaluation mechanism.

The Thonet chair grammar is a two-dimensional parametric shape grammar with thirty-four rules, developed from a corpus of six chairs. The grammar comprises a simplified representation for the curves, similar to the one developed by Terry Knight for the Hepplewhite chairs (Sections 2.2.2.5. and 5.2.2.). The use of a higher abstraction model facilitated the decomposition of the shape into its fundamental principles and simplified the encoding of the functional requirements. The rules focused on the generation of the backrest structure or frame, which was considered the key feature of the design style.

The Thonet chair grammar is the Cartesian product of different algebras. Labels describe the topological relationship between the inner and outer frames. The specific range of solutions codified by the labels followed an analysis of the relations in the corpus and enables topological variation within a finite design space. This condition guarantees the generation of backrest designs with an adequate degree of rigidity. Weights indicate variations in material aspects of the designs. Rule application determined the generation of different designs in the language (Section 5.2.5.). Each resulting topological version constitutes a distinctive topological relationship between the inner and the outer backrest frames.

The second customisation sub-problem is the exploration of preliminary layouts to achieve the customised solution that might become the definitive layout. Exploration occurs in a complementary step through the use of a detailed model. The model represents the three-dimensional geometry, thereby enabling the selection and refinement of shape attributes based on dimensional parameters. This division is important to an industrial designer, because it permits the configuration of a functional preliminary layout through the use of a higher abstraction model followed by its refinement through the use of a detailed three-dimensional model.

The conversion of the shape grammar into a parametric design model to facilitate implementation required the following procedures: a) convert the topological variation space specified by the shape grammar labels into the dimensional search space encoded by the parametric design models; b) translate rectilinear representation into curvilinear representation; c) geometrically represent the remaining chair components; d) establish relationships among the chair components in the reconfigurable model.

A set of parametric design models was implemented in CATIA (Section 5.3.). Each parametric design model corresponds to a distinct topology encoded by the shape grammar. The higher level representation used in the shape grammar was complemented by detailed geometry representing all chair components. Exploration is made by assigning different values to the parameters, thereby creating customised variants (Section 5.3.3.2.).

To summarise, the shape generation subsystem permits the definition of a design language, the generation of multiple topological versions, and the exploration of detailed designs within the language by creating customised variants.

The shape evaluation subsystem follows the shape generation subsystem. Accordingly, evaluation is postponed until after generation and exploration have taken place. In the present research, it is employed to evaluate the mechanical structure of the customised chairs. Therefore, evaluation comprises two sub-tasks encoded as the shape evaluation subsystem: the first is simulation (Section 5.4.), used to calculate the stress in the structure under predetermined operating conditions; the second is optimisation (Section 5.5.), necessary to find the optimal solution of the structure under the specified conditions.

The simulation part, which simulated the ISO standards for testing the structural performance of domestic chairs, demonstrated that a customised variant may or may not be structurally sound due to a small variation of certain parameters' values. Given the possible combinations of parameters, there is a large range of possible solutions, meaning that intuitive and manual testing of these possibilities to reach a better understanding of the solutions domain is a time-consuming activity.

The optimisation part overcame that limitation and guaranteed the automatic search for an optimal customised variant, acting upon the information generated by the previous parts.

The generative design system presented in this chapter aims to enable the implementation of a tailored customisation strategy. Regarding the product family architecture, the generative design system encodes the technological model. In comparison to the conventional models of the design process, it encodes the activities performed in the embodiment design phase of the design process. The encoding of these activities as a generative design system means that the output of the design process is not a single object as it is in mass production, nor a set of different objects, achieved by a combination of predefined components, which takes place in customised standardisation. It is rather a customisable design language, capable of generating several feasible designs. The information generated must be connected to a production system to enable the production on demand of the customised variants and to a frontend application, such as a configurator or an innovation toolkit, to permit the customisation by an end-user.

6. Transformation of the Generative Design System

6.1. Introduction

Knight (1981) defined a formal model for transforming existing shape grammars into new ones capable of producing new design languages. In the model, shape grammars properties such as vocabulary, spatial relations and shape rules can be used as a support for the construction of a new language. The formal model comprises a set of procedures that can be used individually or together to accomplish the new iterative step. The following procedures can be applied either in shape rules or shape schemas: labelling, parameterisation, definition of new relations and shape transposition (also defined as shape equivalence rules.) In shape grammars where languages have been defined through the analysis of a corpus of designs, extending the number of designs provides additional support for transformation (Knight, 1989).

Considering the characteristics of this research, Knight's theoretical propositions can be examined under extended conditions. Transformation can be modelled into the generative design system by the individual transformation of the shape grammar. Functional requirements and tacit knowledge are encoded in the shape grammar, determining the pre-set condition for family identification and reproduction. Furthermore, parametric design models can be refined to encode the new topological versions created by the transformed shape grammar. This enables new simulation and optimisation models to be established. Transformation of the shape grammar can lead to refinement of the remaining parts of the generative design system, which constitutes a new iteration in the development of the system.

The transformation principles defined by Terry Knight are based on information sources that can be categorised as internal or external. One example of an internal source is the refinement of the shape grammar properties, whereas an example of an external source can be the expansion of the corpus. Interpretation, defined here as the ability to analyse, abstract and systematise existing knowledge into another kind of reasoning, plays a key role. Whereas information sources can be either internal or external, there must be an interpretation of the information to support the transformation. In the development of the shape generation subsystem, interpretation was used firstly to encode the Thonet style into shape grammar properties and then to translate the shape grammar into parametric design models. A similar principle can be applied to support the transformation of the shape generation subsystem. However, since the remaining parts of the generative design system have been developed and the requirements for the production system have been established, the transformation of the parametric design models encompasses additional goals.

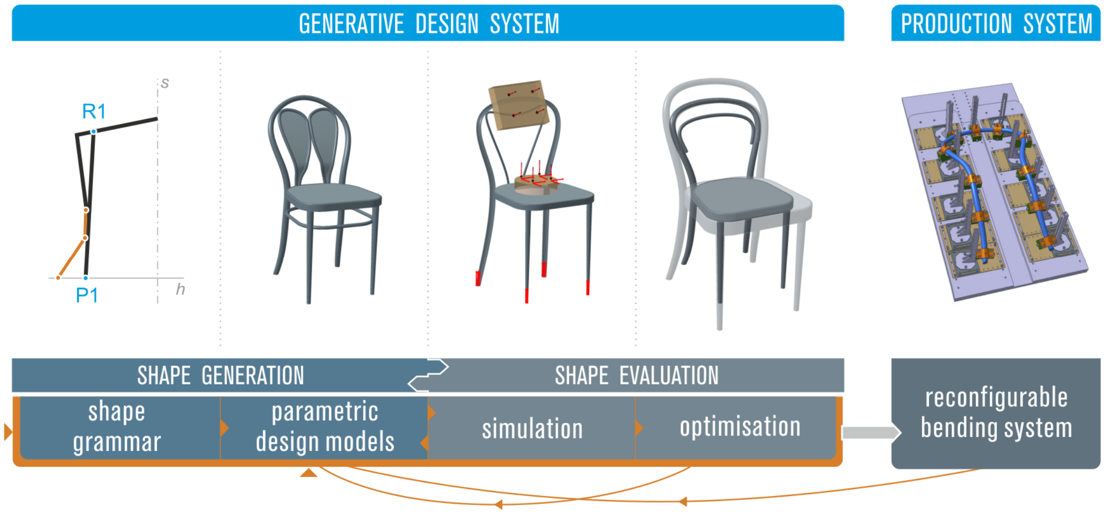

Figure 77. Transformation of the generative design system

This chapter details the methods used in the transformation of the generative design system (Figure 77). The transformation of the shape grammar aims to expand the solution space. The information used to support the transformation is obtained by expanding the corpus (external) and refining the shape grammar properties (internal.)

The transformation of the parametric design models aims to simplify the encoding of the grammar and improve the digital information in order to provide better support for the design process, from design to manufacturing. The orange arrows indicate that both external and internal information sources are interpreted in the transformation of this part.

The simulation part is not transformed, but instead refined. The optimisation part is transformed to include the parameters retrieved from the shape grammar labels, thus providing a closer link between the shape grammar and the optimisation.

6.2. Shape Grammar

6.2.1. Introduction

The Thonet shape grammar (SG1) had two primary goals. The first was to encode the Thonet design style in a generative amenable way. The second was to define a simplified rationale in order to enhance its usability in the design process. The transformation of the shape grammar (SG2) aims to provide a wider range of designs whilst still maintaining the principles of simplification.

The following subsections describe the transformation methodology. A diagram is used to support the analysis of the development of the initial shape grammar. The definition of the diagram leads to reflection on the activities carried out and enables the designer to estimate possible strategies for the transformation in advance. The inclusion of new chairs in the corpus guides the procedure for creating new rules to open up the solution space. The section ends with a comparison of the two shape grammars, in order to understand the extent of the transformation. In addition, the principles of the methodology presented for the transformation are reviewed to enable it to be applied to other product design cases.

6.2.2. The Diagram

Reliable knowledge on the development of the Thonet shape grammar may allow the designer to identify paths for additional creative exploration. A critical assessment of the causes and effects of the decisions taken during the development of SG1 may improve the transformation of the shape grammar, by enabling a strategy to be outlined in advance, the impact of some procedures to be assessed, and the impact of shape grammar properties on the results to be estimated.

These insights led to the development of a diagram that represents the steps in the methodology used to infer the Thonet shape grammar (Figure 78). The goal is to visualise the different steps in the methodology and their associated features and to express the relations between them. A complete overview of the methodology provides the opportunity to analyse each class in detail. Moreover, it becomes possible to understand the dynamic influences that occur across classes, and particularly the influence exerted by each element. The diagram follows some of the organisational principles defined by Noy and McGuiness (2001) in their report on how to create an ontology.

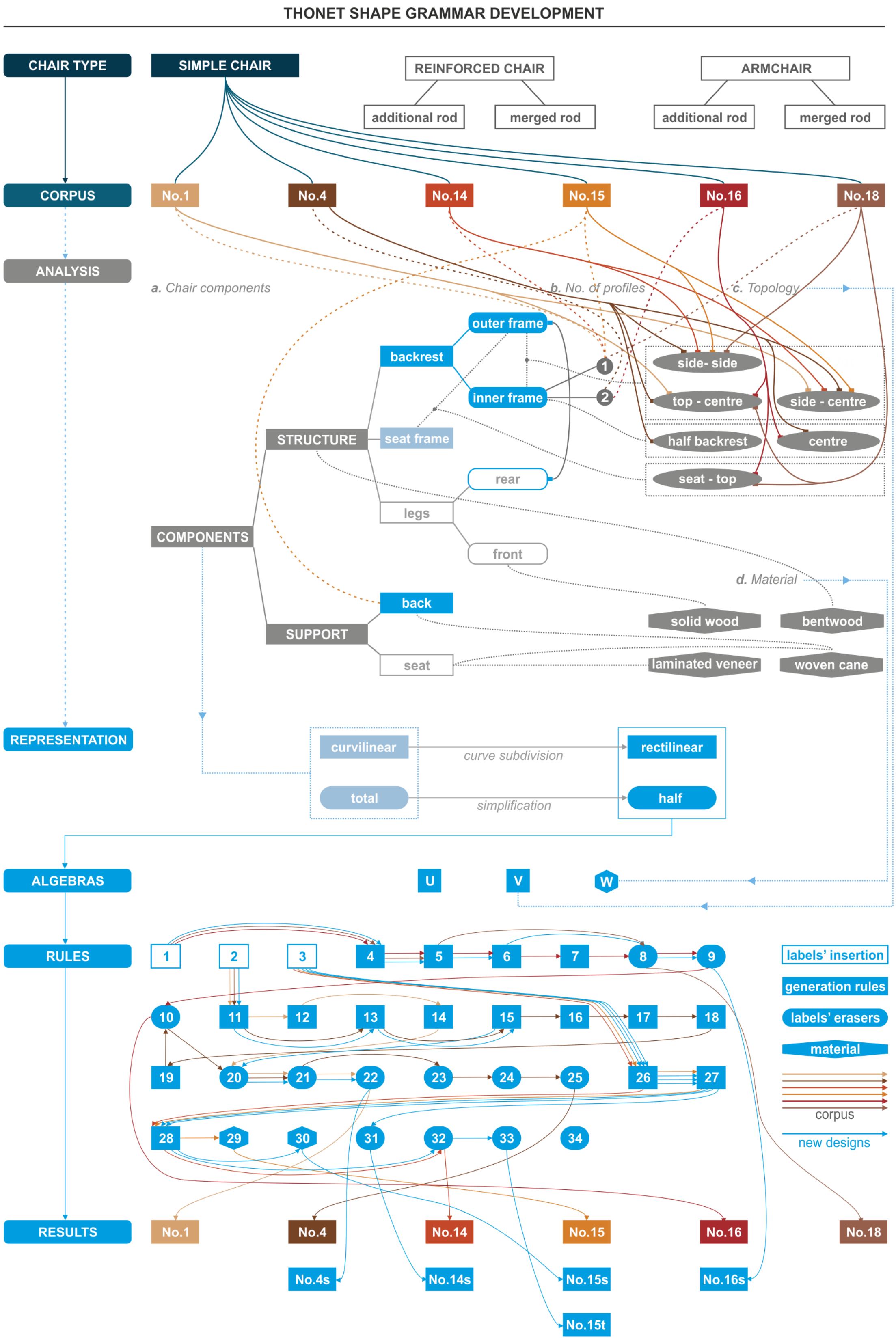

Figure 78. Diagram representing the steps in the shape grammar development

The visual information dissects the procedures of encoding aspects of tacit knowledge from the Thonet designs, which were not amenable to generation, into the shape grammars. The visual variables are divided into classes, elements and interdependencies. Dark blue represents knowledge developed by Thonet, cyan refers to elements fully described by the shape grammar, light blue to elements not directly described, and white to elements not described by the grammar. Information analysed from tacit knowledge is represented in dark grey. The diagram is organised into seven hierarchical classes: chair type, corpus, analysis, representation, algebras, rules and results (Figure 78). These classes are organised as a vertical column on the left-hand side of the diagram. Elements from each class are organised in rows and/or tree structures.

Chair type and corpus refer to tacit knowledge developed by Thonet. Analysis is the decomposition step that supports the knowledge encoded in the shape grammar. Representation, algebras, rules and results illustrate the information encoded and generated by the shape grammar.

Chair type specifies three types of bentwood chairs produced by Thonet[29]. This class only comprises types of chairs in which the side and top rails are merged into a single bentwood piece. The box colour differentiation indicates which types or sub-types of chairs were selected for subsequent steps.

Corpus refers to the individual chairs selected to infer the shape grammar rules. Corpus is a sub-class of chair type and the connecting lines indicate this direct relationship. The box colour differentiation and connections show that six simple chairs were selected.

Analysis defines the class in which the tacit knowledge is interpreted. The results of the analysis are the input information for the shape grammar definition.

The central element of the analysis class is a tree structure representing the arrangement of Thonet chair components (a). The aim of decomposing the chairs into components is to understand their underlying structure and discover which components are assembled and which are merged into a single element. Figure 79 shows the components tree structure for analysing Thonet chairs[30]. The first branch of components distinguishes structure from support. Structure separates out the elements of the frame that give chairs their upright position and support the seat and the backrest above a horizontal surface. Structure comprises legs (rear and front), seat frame and backrest (outer frame and inner frame). The solid connecting line between rear leg and outer frame shows that these components are blended. The dotted lines between seat frame–outer frame and outer frame–inner frame show that the components are connected. Support defines the areas connected to the structure, designed to support the user, comprising back and seat. The box colour and shade show the level of description encoded in the shape grammar.

[29] A detailed description of the three types of Thonet chair can be found in Section 4.2.

[30] The Thonet shape grammar does not describe chair legs. The hooped stretcher rail that connects the legs is therefore not represented in the diagram.

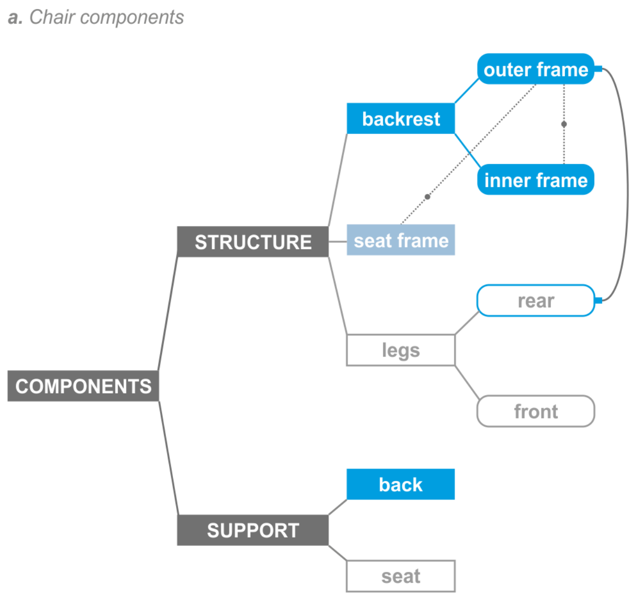

Figure 79. Overview of the chair 'components' tree structure in the 'analysis' class

The components tree is the analysis framework for the chairs selected for the corpus. The analysis indicates the following information: Number of profiles (b) employed in the inner frame; Topology (c), which specifies the type of connection between the inner frame and the remaining components; how material (d) is used in the different chair components. In the diagram, these classes are visually distinguished by shape.

Topology (c) indicates the areas of the chair where there are connections. There are three groups of connections, each associated with a particular set of components in the tree structure. The first specifies the areas of connection between the outer and inner frames. The second indicates connections within the inner frame. The third expresses the connection between the seat frame and the outer frame. The connections are named after the area of the chair in which they are located. Side and top refer to the respective areas of the outer frame. Centre indicates the symmetry axis. Half backrest denotes the inside area of the inner frame, between the symmetry axis and the side area. Seat characterises a connection to the seat frame.

The variables represented in the analysis class are linked to different levels of the diagram. The input comes from the chairs in the corpus and the output is connected by blue dotted lines to representation and algebras. These connections indicate which aspects of tacit knowledge are incorporated into the shape grammar properties.

The connections between analysis and corpus are explained by detailing Chair No.15 as an example:

Chair components (a) in cyan indicate that the backrest (outer and inner frames) and the back support will be directly explained by the shape grammar;

Number of profiles indicates (b) that the chair has one such element;

Topology (c) expresses two types of connection between the outer frame and the inner frame. These connections are side–side, referring to two screws that attach the inner frame to the outer frame, and side–centre, indicating that the inner frame is visually connected to the symmetry axis.

Material (d) shows that the whole structure is made from bentwood. The front legs are fabricated in solid wood, and the seat frame can have a support panel made out of laminated veneer or woven cane. The back support is made of woven cane.

Representation is the first step in the shape grammar definition. Shape simplification comprises two levels, each characterised by two layers. The curvilinear representation of Thonet chairs becomes rectilinear through curve subdivision. Due to bilateral symmetry, only half of the design is represented. Following the colour scheme previously defined, cyan indicates that half-rectilinear representation is the one used in the Thonet shape grammar. The final element connects to the algebras class.

Algebras indicate the Cartesian definition of shapes, categorised under U, V and W. The U algebra describes all the component shapes. V characterises topology. Algebra W determines how bentwood, laminated veneer and woven cane are used in the fabrication of chair components.

Rules indicate the thirty-four rules that constitute the shape grammar (Section 5.2). The differentiation of the rule types appears on the right-hand side. Arrows in different colours show the rule application sequence in the generation of designs.

Results lists possible designs generated by rule application. The first row designates chairs from the corpus. The cyan boxes in the next rows represent new designs, named and positioned after similar chairs in the corpus.

6.2.3. Transformation Strategy

The development of the diagram required thorough reflection on the procedures used to define the shape grammar. This enabled the different types of design thinking employed in the different procedures in the methodology to be understood and mapped. There is a dynamic relationship between analytical reasoning, focusing on understanding what things are, and creative thinking, focusing on what things should be. Predictive reasoning is the third type of design thinking. It is involved in shape grammar rule development and refinement. The difference between predictive reasoning and creative thinking is that the focus is not on the direct consequence of rule application, but rather on the possibilities it might enable by interacting with other rules. The dynamic relationship between these types of design thinking determines the shape grammar rule development and refinement.

A critical assessment of the diagram provided a comprehensive understanding of elements and relations. It clarified the role each element plays in the corresponding class and its influence across classes. These activities determined the strategy for the transformation of the shape grammar. The main purpose of the transformation is to overcome the deterministic nature of the grammar and should allow for a larger set of novel solutions. The strategy employed in the following experiment is incremental.

"Incremental transformation observes changes to the source. It then translates those parts of the source that change the target. It creates elements in the target if such elements do not exist, it modifies elements if such elements exist but have changed, and it deletes elements" (Johann & Egyed, 2004, p. 363).

The transformation requirements were defined on the basis of the critical assessment. The shape grammar simplification principles were maintained, together with the syntactic interpretation of the corpus defined in the representation, since it provides the smallest set of elements for representing curves.

According to the diagram, the chair type shows that the selected chairs in the corpus belong to the same type. Furthermore, it shows that reinforced chairs and armchairs share the same configuration sub-types. During transformation, a new chair will be selected from one of the other remaining sub-types. This will provide new topological relations between chair components, which consequently influence algebra V, leading to new rules and results.

An overview of the rules and results demonstrates which rule initiates the greatest number of solutions. Rule 1 and Rule 2 both initiate three designs and Rule 3 initiates the design of five solutions, three of which are new. Further observation shows that the subsequent Rule 26 is the only rule that proposes two points, instead of one. The number of solutions is also directly related to the material selection options. In order to achieve greater interaction between rules, a new rule that draws a two-point segment is created. This new type of connection will be observed in a new chair.

The first shape grammar version (SG1) generated twelve solutions (excluding solutions with embedded segments) from a corpus of six chairs. Adding two chairs, with new types of connection should open up the solution space to include at least up to fifteen solutions.

6.2.3.1. Overview of the New Chairs

Two chairs are added to the corpus to support the transformation of the Thonet shape grammar (Figure 80). The diagram shows the formalisation of these elements and their analysis (Figure 81).

Chair No.3 is similar to Chair No.15[31], selected in the previous development. Both chairs share the same components and a similar configuration. The difference between them is that the Chair No.3 inner frame has an adjacent connection to outer frame top area, resulting in a new topological relation (side–top), which was not described in SG1.

[31] Additional details on Chair No.15 can be found in Section 4.4.

Figure 80. Chair No.3 and Chair No.19 selected for the corpus (Source: Bangert & Ellenberg, 1997, p. 42-43)

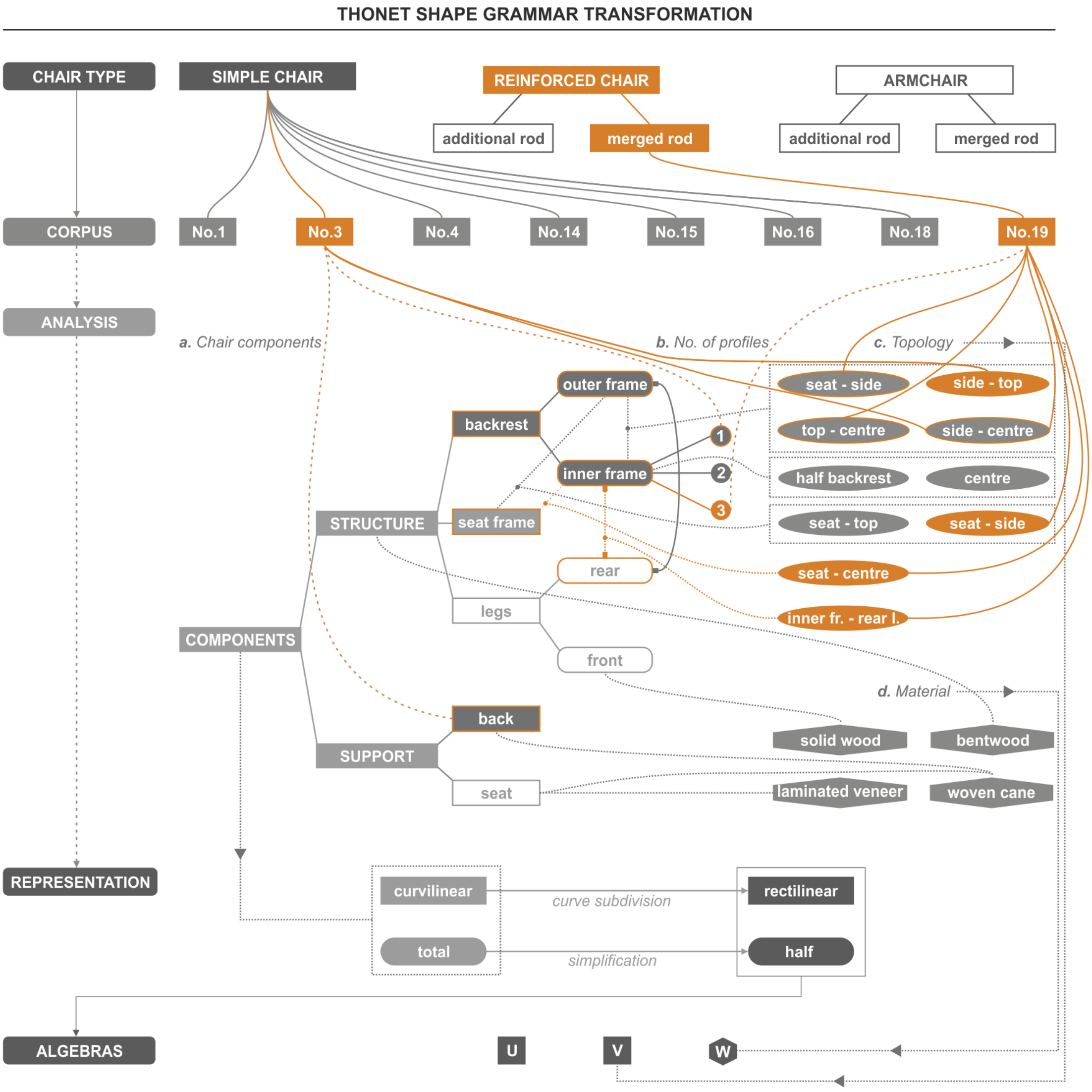

Figure 81. Overview of the new elements in the diagram

Chair No.19 is a reinforced chair with a merged rod. This configuration is new in comparison to the remaining chairs. In the diagram, the configuration is formalised in the analysis class, specifically in the chair components (a) tree, number of profiles (b) and topology (c). In the chair components (a) tree there are two new categories of connection between components: 1) a connection between the inner frame and seat frame; 2) the merging of the inner frame and rear legs. The first is formalised in the topology (c) as seat–centre and the second as inner frame–rear leg. The analysis shows that there is a change in the inner frame properties. In Chair No.19 the inner frame becomes the main backrest structure and therefore possesses properties similar to the outer frame in simple chairs. Furthermore, the diagram indicates that there is a connection between the seat frame and the side area of the outer frame. Chair No.19 comprises three inner frame profiles.

New features observed in Chairs No.3 and No.19 constitute the basis for the transformation of the shape grammar.

6.2.3.2. New Rules

This subsection details the transformation of the shape grammar properties. The rules and the preconditions required for their application will be compared to the previous development of the shape grammar. The goal is to provide a better understanding of the extent of the transformation.

Preconditions for the use of the shape grammar guide the user during the rule application by preventing the generation of solutions with embedded segments or incomplete inner frames. The initial shape is a simplified representation of half of the backrest structure with an indication of the axis of symmetry *s* and the horizontal segment *h* showing the position of the chair seat. The auxiliary 4 x 4 grid designates the position where labelled points and segments can be positioned. Label letters and numbers are positioned from left to right and from bottom to top. The labelled points P, Q, R and S must be embedded in the labelled segments a, b, c and d, respectively. Every point position is parameterised under the respective segment length.

Rectilinear segments cannot cross one another. Rules that allow for the design of labelled segments S2-S1' e S1'-t' can only be applied if S2 is not connected to P or Q. Every design with an enclosed area can have a support panel made out of woven cane or laminated veneer, as the rules only specify the most common designs. In order to complete the generation procedure, a minimum of three points must be erased. The design must be reflected along the symmetry axis *s* to obtain a complete chair design and then translated into a curvilinear representation. The procedure is concluded with the removal of segments *s* and *h*.

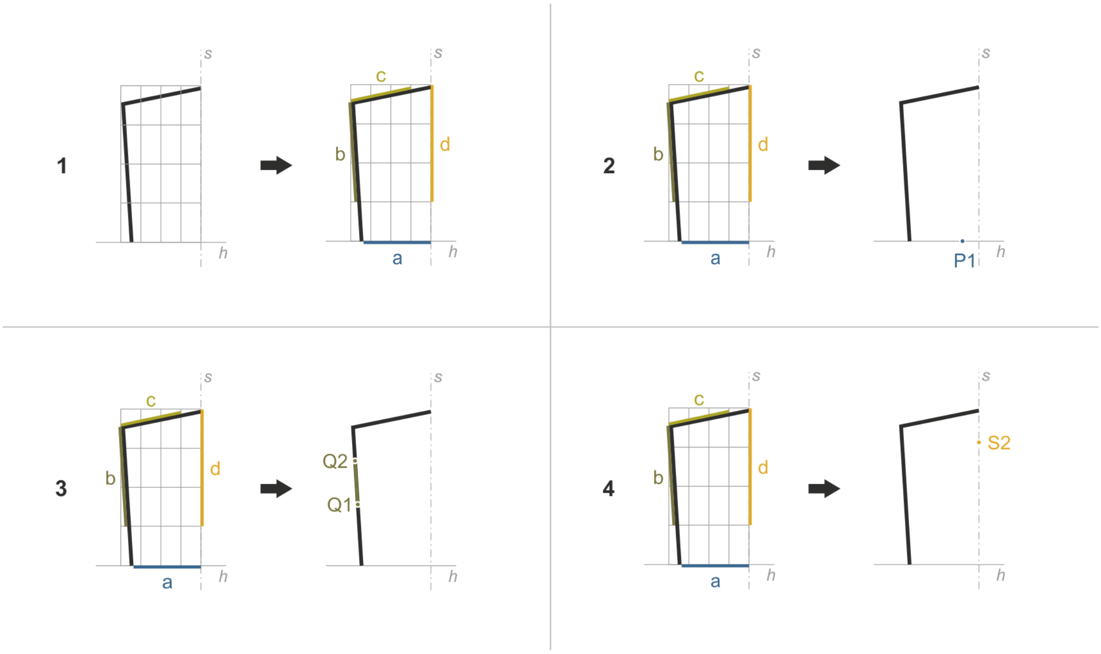

Figure 82. Rules 1 to 4

Rule 1 (Figure 82) introduces the initial shape, represented in an auxiliary grid to position the labelled segments. The labelled segments that define the space for topological variation comprise additional space, when compared with those in SG1. Their extension follows the analysis described above.

Rules 2, 3 and 4 configure the first points that define the type of connection between elements.

The seat-centre rule category (Figure 83) provides a novel type of connection between the seat frame and backrest centre (symmetry axis). This connection is made possible by the interaction between two sets of points which accommodates the existence of multiple segments. The design principles of Chair No.19 (Figure 80; Figure 81) were the foundation for this category of rules.

Rule 10 (Figure 84) is an update of an existing rule to conform to the new labels definition. It expresses the connections between the seat frame and the outer frame. Rule 11 is a new rule that describes the seat-side connection. Combined with other rules, it allows for the generation of designs containing segments connected to all possible areas: the seat frame, outer frame side area, outer frame top area and symmetry axis.

The relationship between the top backrest area and the symmetry axis (Figure 85) was further explored by increasing the length of the labelled segment d. Like Rule 10, Rule 12 is a redesigned rule. Rule 13 is a shape equivalence rule, mandatory if point S2 is positioned below the first quarter of the auxiliary grid. This rule adds two segments with an inferior weight, which (when translated into curvilinear representation and fabrication) will define a circular shape produced with layers of wood veneer. This solution guarantees the rigidity of the chair and is verifiable in later Thonet chairs, such as the No.19.

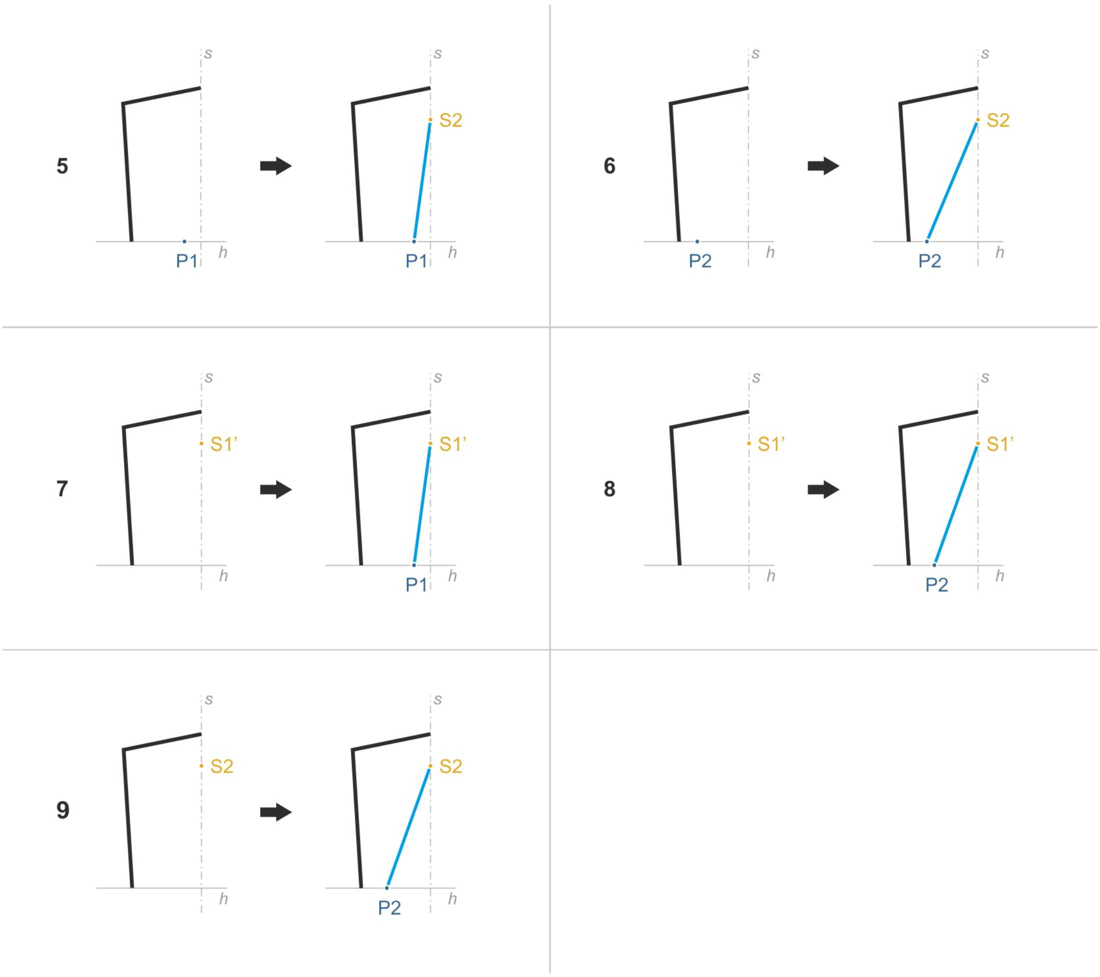

Figure 83. Rules 5 to 9

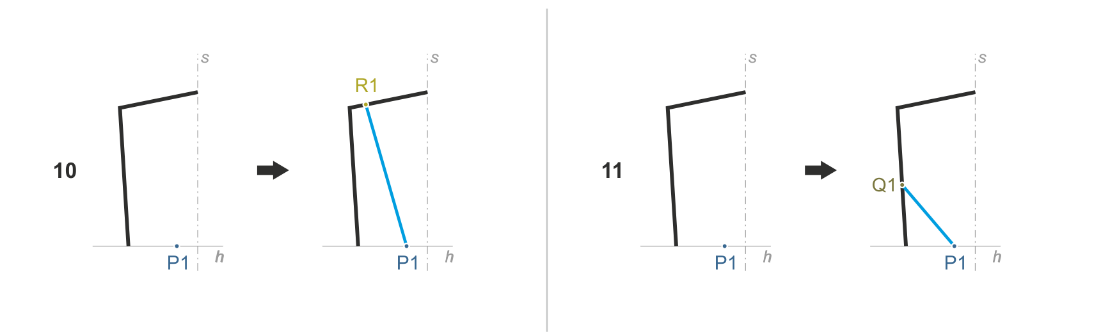

Figure 84. Rules 10 and 11

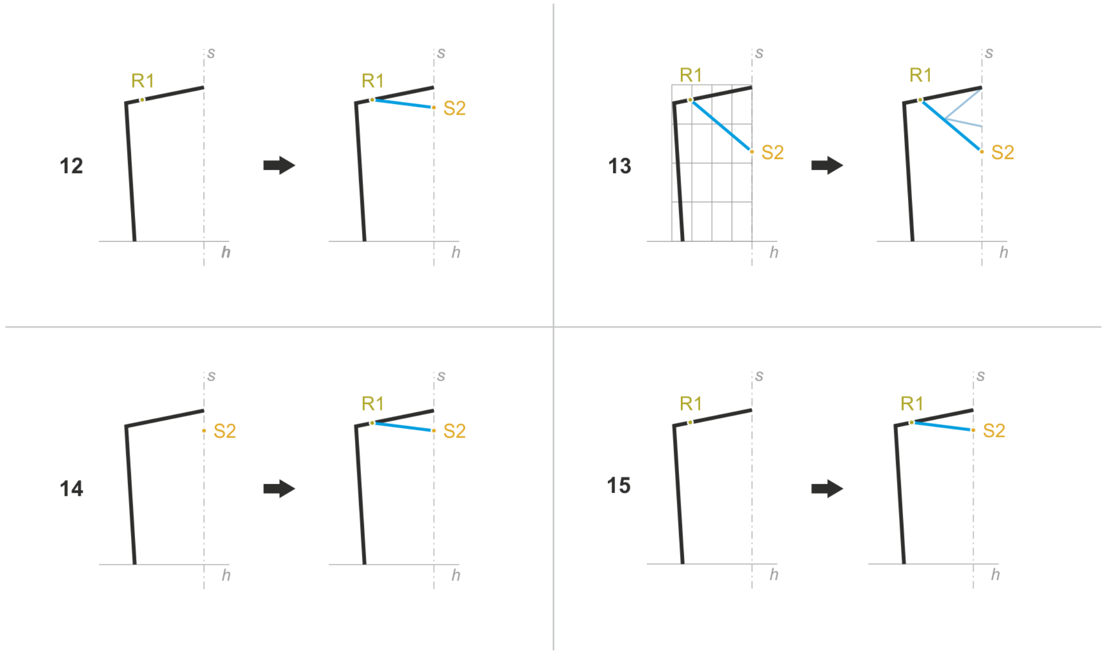

Figure 85. Rules 12 to 15

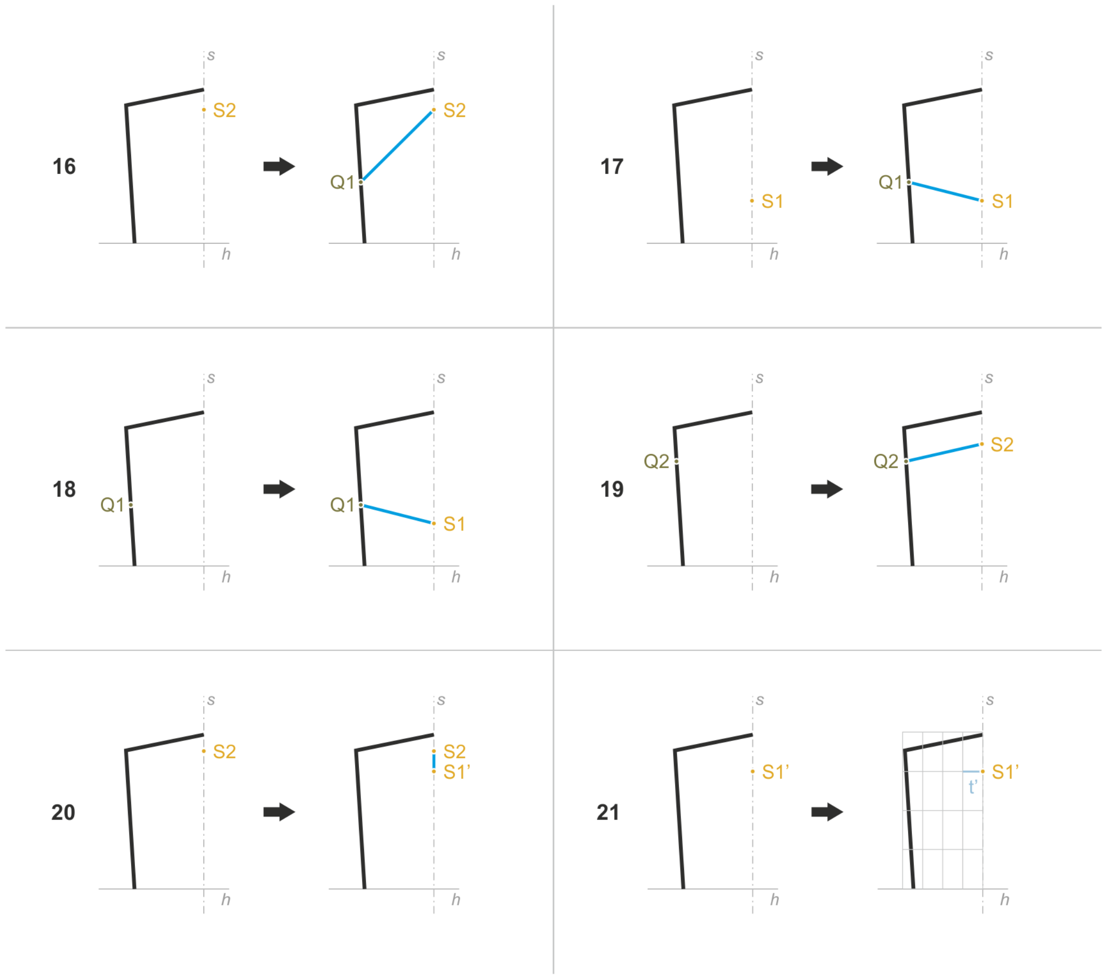

Figure 86. Rules 16 to 21

The categories for the connection between the backrest side and the symmetry axis (Rules 16 to 19) and between the segments in the symmetry axis (Rules 20 and 21) existed in the previous shape grammar version (Figure 86). The simplification of labels in SG2 reduced the number of rules in comparison to SG1.

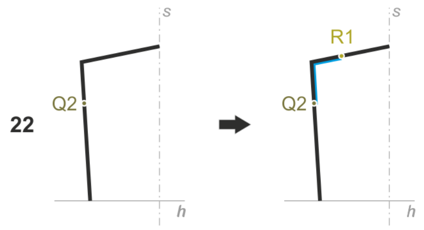

Figure 87. Rule 22

Rule 22 (Figure 87) constitutes a new category, defined after the analysis of Chair No.3. It is characterised by the connection between the outer frame side area and its top area. It provides further exploration of the rules containing point Q2.

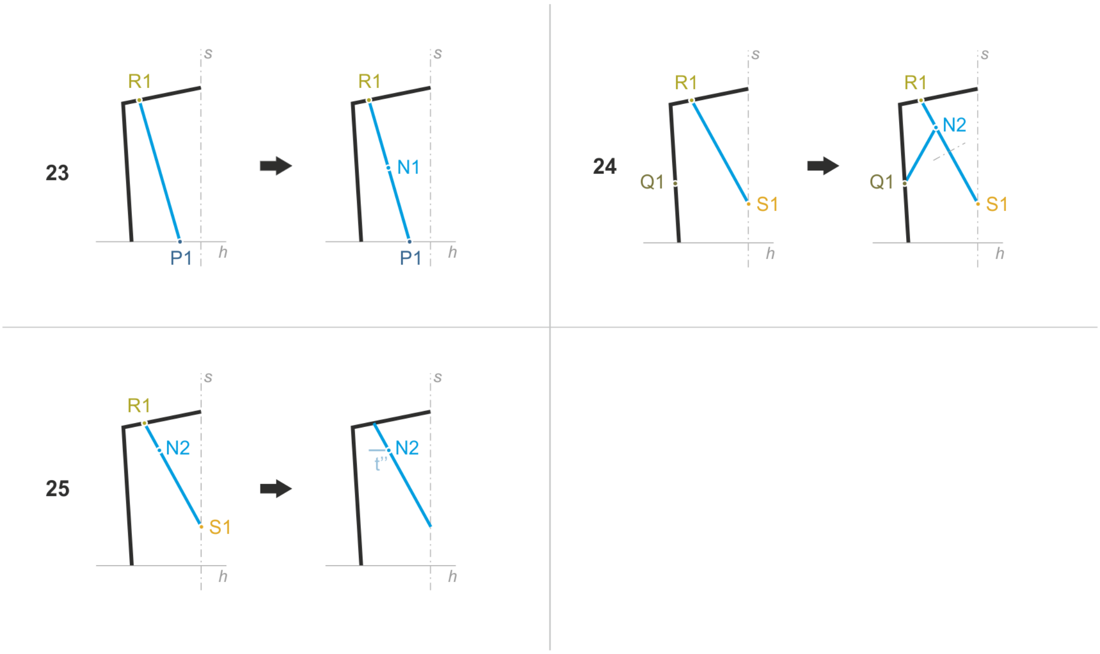

Figure 88. Rules 23 to 25

The half backrest category (Figure 88) was extended with Rule 23. This rule enables designs containing segment P1-R1 to be further explored. Point N1 is a parametric control point for the spline, allowing greater control of the curves generated. This rule derives from an analysis of the encoding procedures in the parametric design models (Section 5.3.3.1.). The remaining rules in this category are redesigned.

The rules for weight assignment in closed areas (Figure 89) specify the selection of the covering for inner frames with enclosed areas. Lighter and dark shades of grey define woven cane and laminated veneer, respectively. They were revised to respond to a larger number of possible designs. However, as mentioned in the preconditions for rule application, these rules express the most common configurations, but their principles may be applied to every solution that includes enclosed areas.

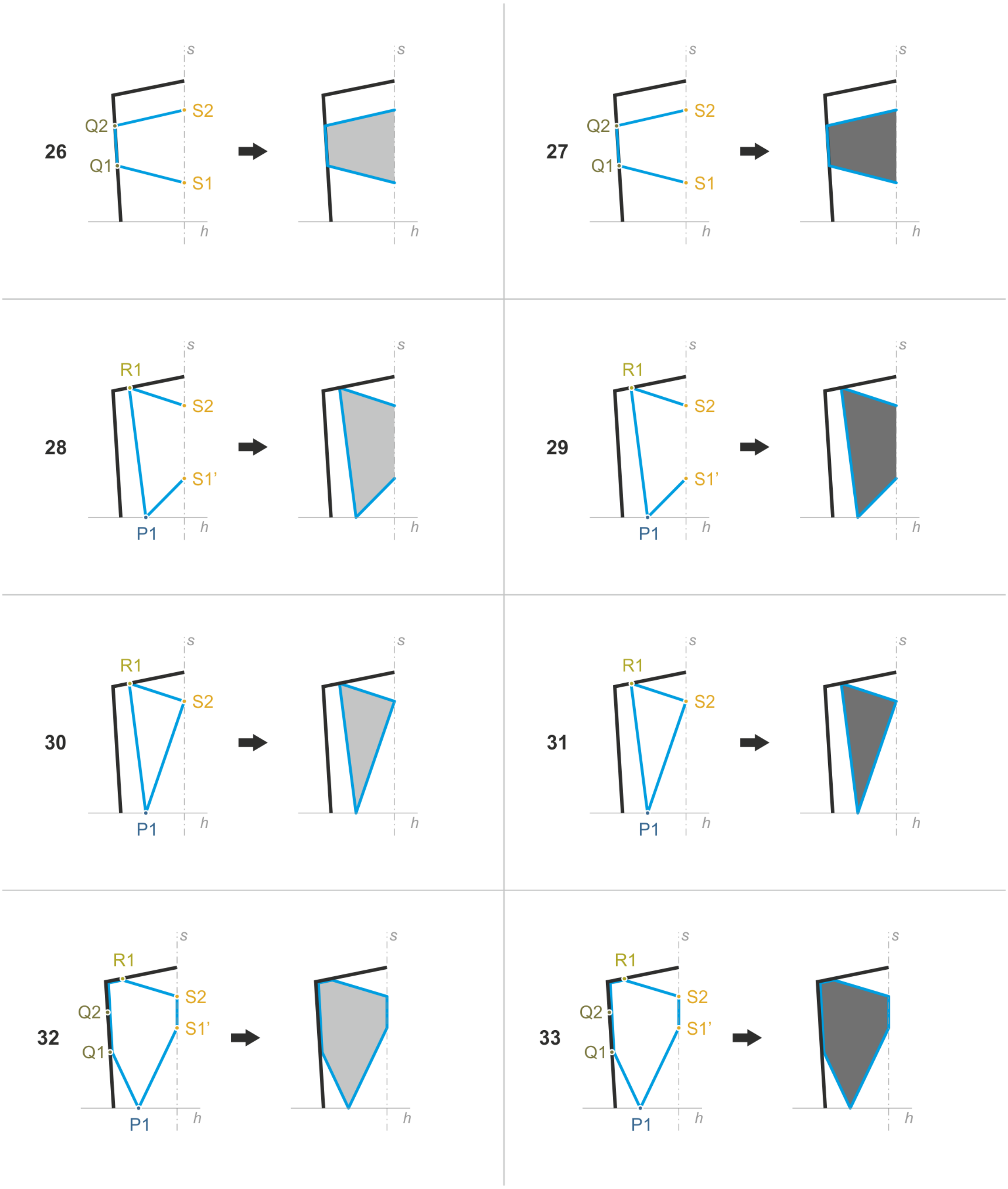

Figure 89. Rules 26 to 33

Rule 34 (Figure 90) describes the structural changes observed in Chair No.19. This new rule can be applied if point P1 is coincident with the outer frame. The rule application adds weight to the interior segment P1-R1, transforming it into a structural component. The outer frame changes and is now composed of four segments, two with maximum weight and two with intermediary weight. They transform the outer frame into a structure which is adjacent to the inner frame and connects with the seat frame (*h* segment).

This rule could be complemented with a side view for better definition of the solution, which creates space for the additional development of the shape grammar rules and properties.

Rules 35 to 46 erase labelled points and segments (Figure 90). According to the preconditions, erasing three labels at once prevents the generation of incomplete chair designs.

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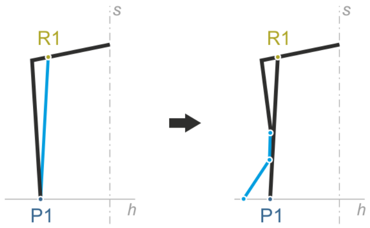

35 <sØ, {(0,0): P1}> → <sØ, Ø>
36 <sØ, {(0,0): P2}> → <sØ, Ø>
37 <sØ, {(0,0): Q1}> → <sØ, Ø>
38 <sØ, {(0,0): Q2}> → <sØ, Ø>
39 <sØ, {(0,0): R1}> → <sØ, Ø>
40 <sØ, {(0,0): S1}> → <sØ, Ø>
41 <sØ, {(0,0): S1'}> → <sØ, Ø>
42 <sØ, {(0,0): S2}> → <sØ, Ø>
43 <sØ, {(0,0): N1}> → <sØ, Ø>
44 <sØ, {(0,0): N2}> → <sØ, Ø>
45 <sØ, {(0,0): t'}> → <sØ, Ø>
46 <sØ, {(0,0): t''}> → <sØ, Ø>

Figure 90. Rules 34 to 46

6.2.3.3. New Designs

In comparison to the initial grammar, the transformed shape grammar enables designs in the original corpus to be generated and a wider range of solutions. Figure 91 shows a sample of new designs[32].

[32] The solution naming indicates three rules applied after Rule 1. The letters XYZ indicate the second rule applied, which can be 2, 3 or 4. The numbers which follow describe the other two rules and a further distinction is made with letters. This type of naming facilitates the tracking of information between shape grammars and parametric design models which follow the same naming system.

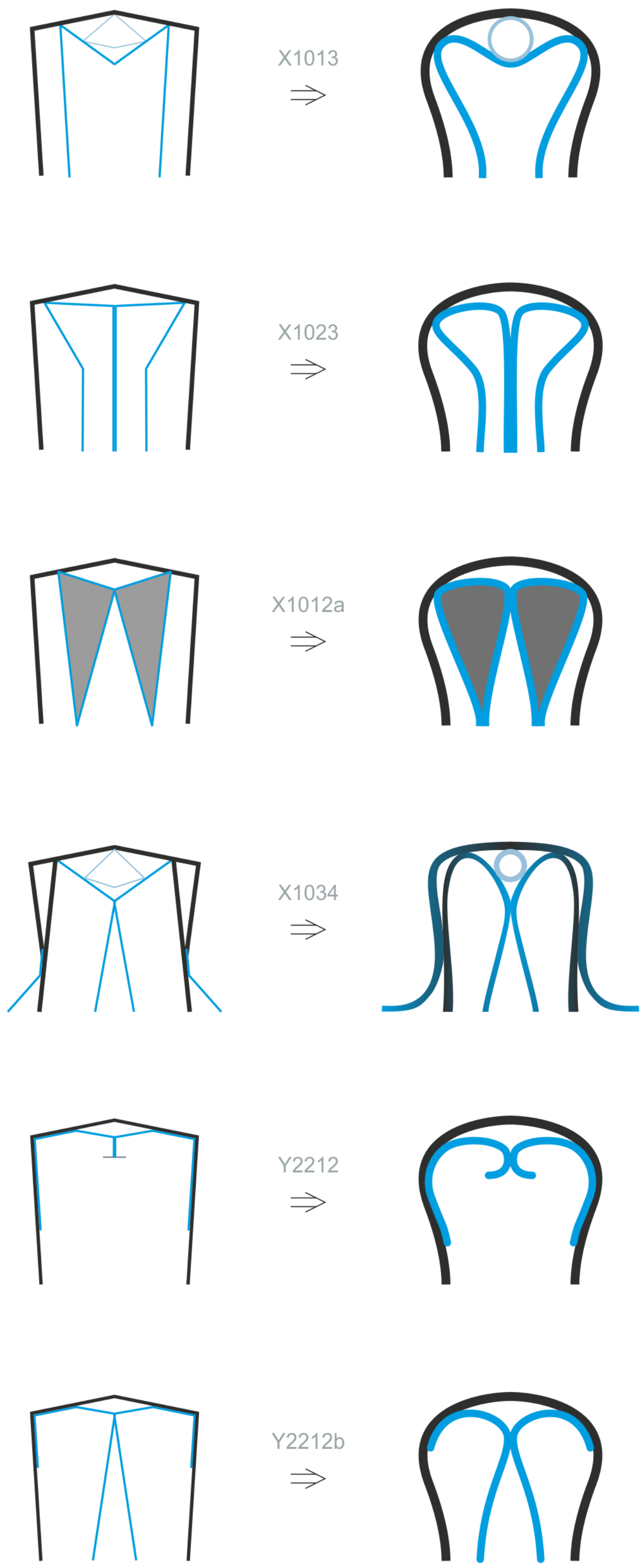

Figure 91. New designs

6.2.4. Comparison of the Initial Shape Grammar and the Transformed Grammar

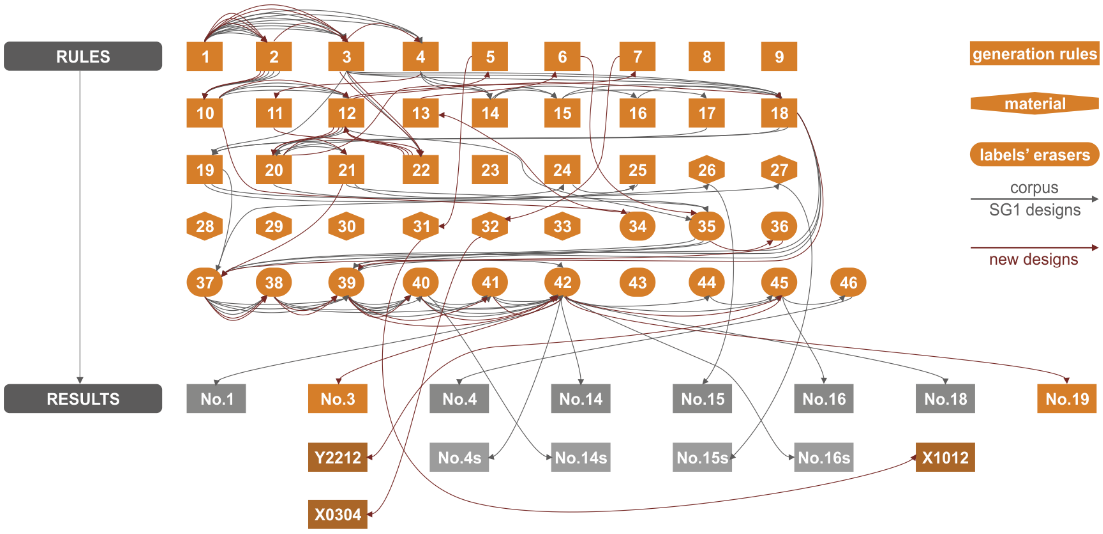

Figure 92. Rules and overview of results

A comparison of the two diagrams synthesises the transformation results. Since the algebras and representation were not transformed, the comparison focuses on rules and results.

Figure 92 illustrates an overview of the SG2 rules and results. Orange indicates the span of transformation. All the rules were redesigned and when applied generated an increased number of new designs, in addition to the two selected chairs. The diagram shows five new designs (for the purposes of simplification), although the shape grammar transformation allows several more solutions[33] to be generated, as indicated in Figure 91.

The initial shape grammar development comprises thirty-four rules, whereas the transformed grammar includes forty-six rules. The SG1 rules may be categorised as follows: nineteen rules for generation of basic designs, two rules for the selection of coverings and thirteen rules for the deletion of labels. SG2 encompasses twenty-six rules for generation, eight rules for selection of coverings and twelve rules for label deletion. SG1 generates a total of eleven designs, while SG2 generates at least thirty designs.

The larger number of designs in SG2 relates to two factors: 1) the larger number of rules for the selection of coverings; 2) the description of additional types of connections. Although the first factor correlates directly with the number of solutions generated, the second needs closer analysis. SG2 comprises seven additional generation rules in comparison to SG1 (twenty-six, as opposed to nineteen.) In addition, their organisation is different, leading to a difference in the number of solutions generated. SG1 comprises three sets of labels that determine the application of a specific set of rules. This type of organisation, with a unidirectional generation procedure, makes the structure of the grammar deterministic. This condition is observable in

[33] Appendix 1 shows additional solutions generated by the grammar.

Figure 78, which shows the interaction of the rules in the generation of the designs. In SG2, this condition was optimised. The labels were made common to all rules, thus permitting greater interaction during rule application. Moreover, the rules describe additional types of connections between backrest components. The combination of both features contributes to the generation of an increased number of solutions. These features can be seen in the diagram (Figure 92).

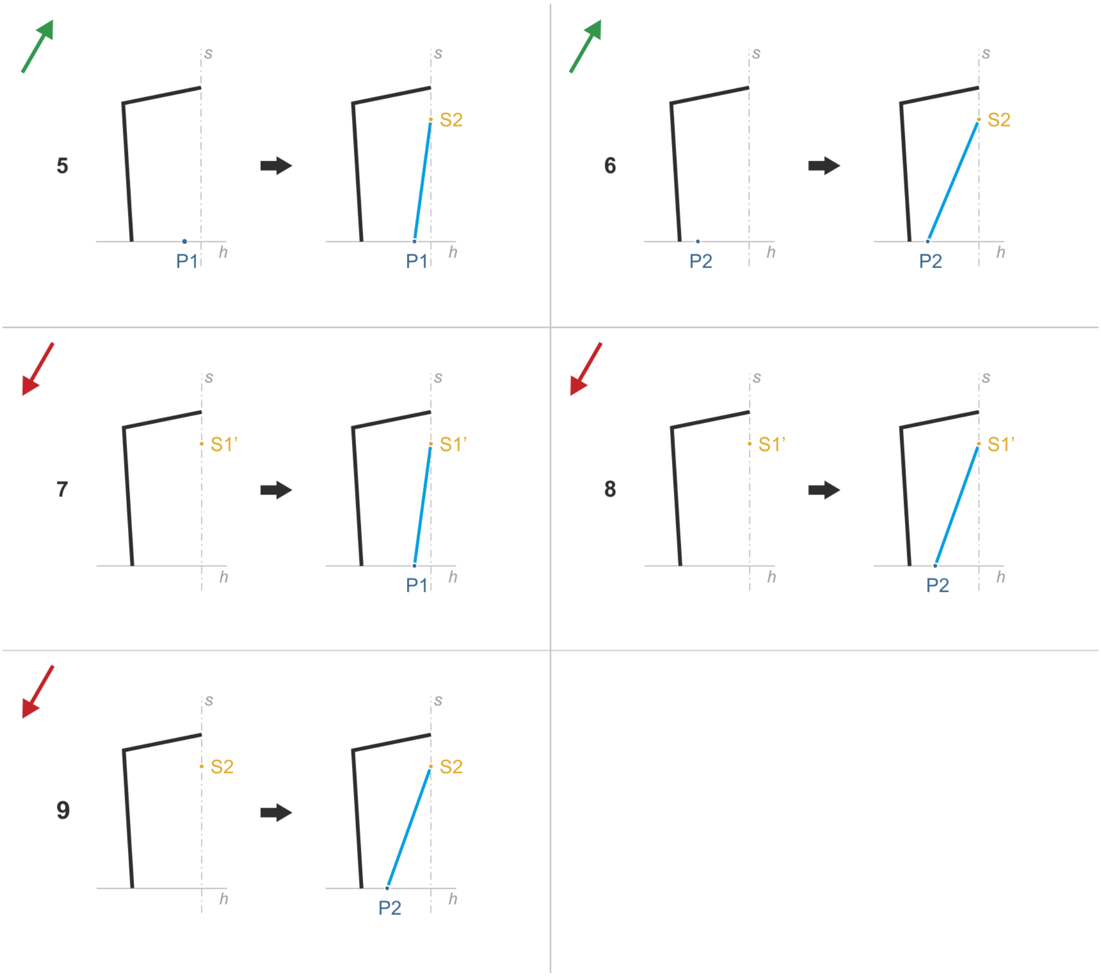

Figure 93. Indication of direction in the seat-centre category of rules

Rules describing additional types of connections require additional experimentation to maintain a smaller number of rules in the grammar and exclude redundant solutions which produce the same composition using a different combination of labels. Predictive reasoning guides the rule interaction refinement process. The explanation of the seat-centre type of connections illustrates this premise (Figure 93). This category of rules contains the following labelled points: P1, P2, S1' and S2. From the eight possible connections between the seat frame and the symmetry axis, five were formalised as rules. The refinement process estimated the potential interaction between sets of points according to the following activities: 1) assessment of a satisfactory trade-off between number of rules and number of possible solutions; 2) evaluation of connections that might lead to incomplete inner frames; 3) avoidance of conflict with other rules.

6.2.5. Discussion

The methodology for transforming the Thonet shape grammar included the development and use of the diagram. The diagrammatic representation clarified the steps in the methodology, the properties of the original Thonet design style and how they were encoded in the shape grammar properties. It also helped estimate possible strategies for transformation. The construction of the diagram requires reflection on the steps taken, a condition that fulfils the goals presented by Schön (1983).

The initial shape grammar had well-defined properties, in particular, a clear vocabulary and clear algebras. These properties were defined as constraints in the transformation strategy. As both domains and constraints were clearly identified, there was a reduced conceptual space for improvement. The methodology proved to be suitable for dealing with these features, thereby supporting decision-making during the transformation. It was possible to start with a solid functional state and evolve to a fluid state to accommodate change. The diagram enabled the designer to map spaces and estimate places for new layers of information. The activity of encoding new layers of complexity requires a return to ambiguous reasoning that fosters new approaches. One advantage of the proposed methodology is that it allows for estimation of these exploration procedures.

The diagrammatic representation contributed towards achieving the goal of incremental transformation. This type of strategy is consistent with the goal of broadening the solution space and maintaining some of the previously defined principles. Incorporating two chairs into the corpus led to more solutions, and labels common to all rules provided additional interaction between rules.

The experimentation presented in this section provides a methodology that can be used in other shape grammar cases. The specific tailoring to Thonet shape grammar conditions was achieved by focusing on topological relations between components and material description. A similar methodology can be followed for its application to other shape grammars, by tailoring to accommodate specific conditions. To summarise, the methodology consists of: 1) listing all the activities performed by the designer during the development of the shape grammar; 2) categorising the activities into classes; 3) defining the elements in each class; 4) establishing relations; 5) designing a vocabulary of visual variables; 6) testing and refining the diagram.

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6.3. Parametric Design Models

6.3.1. Introduction

Parametric design models constitute the second part of the shape generation subsystem and are linked to the shape evaluation subsystem. Their structure derives from the interpretation of the shape grammar, which represents the input information, whilst the output information connects to subsequent steps in the design process. Parametric design models therefore become a central repository of information and meet several goals at once. They allow for accurate representation and customisation of grammar-based designs for design exploration, visualisation, analysis, and fabrication.

When the parametric design models were transformed, the shape evaluation subsystem had already been developed and initial tests for the production system were being set up. Furthermore, additional Thonet-related information had already been accessed, specifically, the Thonet 1904 Catalogue and official CAD models (Thonet GmbH, 2013).

Given this, the goals of the transformation included: 1) improving the internal structure by implementing a new interpretation of the shape grammar rationale, 2) refining the internal structure to optimise the shape evaluation and data organisation to support fabrication.

This section presents the methodology for the transformation of the parametric design models encoding the Thonet shape grammar, which comprises the following procedures: analysis, critical assessment, experimentation, and implementation. Implementation is detailed in a description that highlights the differences between former models, to provide a clear understanding of the extent of the transformation. A formal comparison between the initial parametric design models and the current implementation is then presented, with the aim of discussing the advantages and disadvantages of the two sets of models. The section concludes with a reflection on the role of parametric design models in the development of a generative design system for mass customisation in the furniture design industry.

6.3.2. Analysis

The information that supports the transformation of the parametric design models was inferred following an analysis that focused on the input information, digital information and output information of the parametric design models. The input information relates to the tacit knowledge embodied in the original Thonet chairs and the explicit knowledge encoded into the shape grammar. The digital information relies on a comparison between an official STL model of a Thonet chair and the initial parametric design models. The output information includes an assessment of the information generated and its connection to the simulation part, optimisation part and production system. The results of this inquiry provided the requirements that led to experimentation, followed by the final implementation of the parametric design models.

6.3.2.1. Thonet Catalogue

The Thonet 1904 Catalogue, issued forty-five years after the first in the series, was the largest catalogue issued by the company to date. The book edition (Thonet Company, 1980) contains supplementary material from the 1905, 1906 and 1907 catalogues. In addition to technical information, it provides an extensive collection of designs, some containing minor refinements of the originals.

A selection of data was further analysed and used to support the transformation of the parametric design models. The selection focused on bentwood chairs – standard models, reinforced models and armchairs – and canapés in which the side and top rails are merged into a single bentwood piece. The inclusion of canapés is not directly related to the initial goals of the research, but reflects the statement on future work presented in the discussion of the shape grammar (Section 5.2.6).

One hundred and twenty-three models were analysed from the catalogue. The selection comprised models which were similar to the ones generated by the shape grammar and the parametric design models. It was found that the seat shape evolved from round to trapezoidal: a total of eighty designs had a trapezoidal shaped seat, as opposed to forty-three with a round seat. It was also observed that a seat with this configuration was used in the canapé designs. On the basis of this analysis, it was decided to include a trapezoidal seat shape in the parametric design models.

6.3.2.2. Shape Grammar Interpretation

The transformed shape grammar (SG2) followed the same principles used in its initial development (SG1). The first parametric design model implementation (PM1) comprised a direct translation from analogical rectilinear representation to a digital rectilinear representation encoded on the vertical plane. Although a similar approach could have been followed to implement the transformation of the parametric design models (PM2), a new interpretation was adopted in order to allow for comparison with the first implementation. The implementation of PM2 is therefore based on a direct interpretation of the shape grammar schema into a curvilinear parametric design (Figure 94).

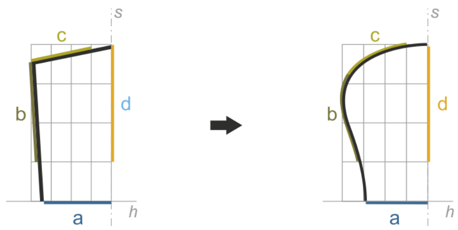


Figure 94. Curvilinear representation of the shape grammar schema

6.3.2.3. Digital Information

An official STL model from Thonet GmbH, which features a trapezoidal seat and simplified tapered front legs, was analysed and compared with an equivalent configuration in PM1. The aim was to assess the degree of faithfulness generated by parametric design models, particularly the accuracy of curvilinear representations.

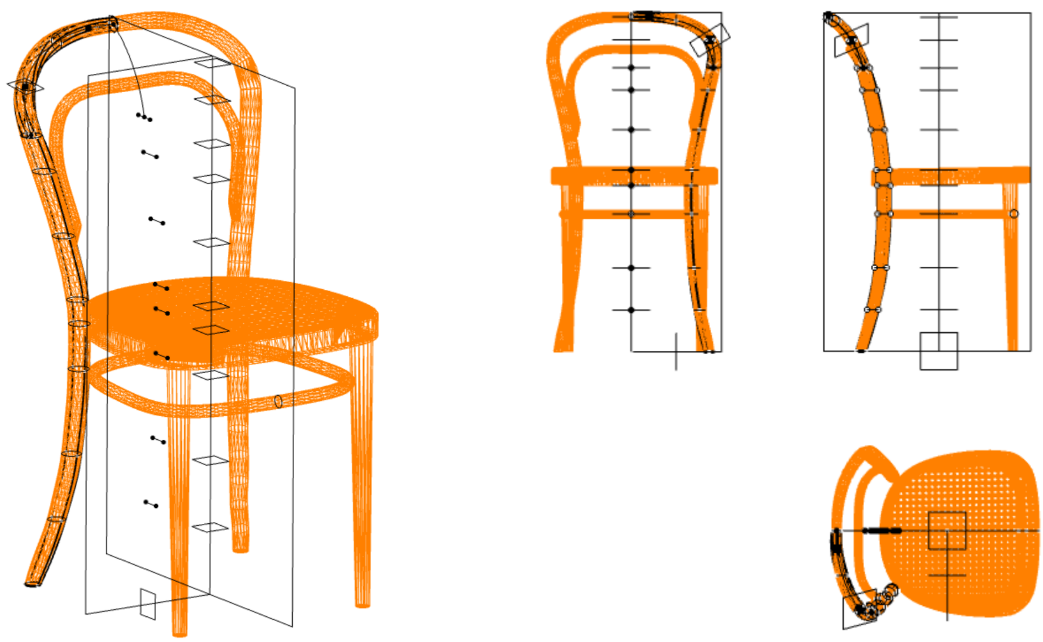


Figure 95. Official Thonet STL model analysis

The analysis involved developing an equivalent surface-based model of the STL model (Figure 95). This activity provided a better understanding of the geometrical description of each component and the topological relationships between components. This information supported an experimentation stage which focused on: a) refining topological mathematical equations; b) testing different NURBS definitions; c) developing a new internal organisation for geometrical information; d) creating new relationships between dependent and independent parameters.

Manual parametric variation of several features informed the organisation of the parametric design rationale. The experimentation also included the use of parametric model information to conduct FEM tests and fabrication tests.

6.3.2.4. Summary of Requirements

The results of this analysis provided the requirements for encoding the parametric design models. They included enhancing their internal structure, better aesthetic conformance, easier implementation of the different topological versions generated by the shape grammar, data better suited to performance-based models, and better decomposition of components for fabrication.

PM1 is encoded in a single geometrical body. This condition is suitable for the exploration of customised variants but is not practical in terms of providing information about the different components for the production system. The PM2 internal organisation features separate components of the chair structure. Considering data suitability for the subsequent steps of the design process, each component is modelled in a separate geometrical body. This breaks up the interrelated equations between different components, creating the need for a modular approach to optimise the organisation of the parametric design models. The modular approach is based on geometrical sets used to describe chair components. These geometrical sets modularise the required auxiliary geometry and operations that support the final definition of a construction element.

The outer frame offers better NURBS control and a variable cross-section description which is observable in the original Thonet chairs. A trapezoidal seat frame was encoded, whose definition includes additional components such as the frame, corner blocks and seat panel. The representation of the chair components includes the detailed geometry of assembly features such as holes, mortises and grooves.

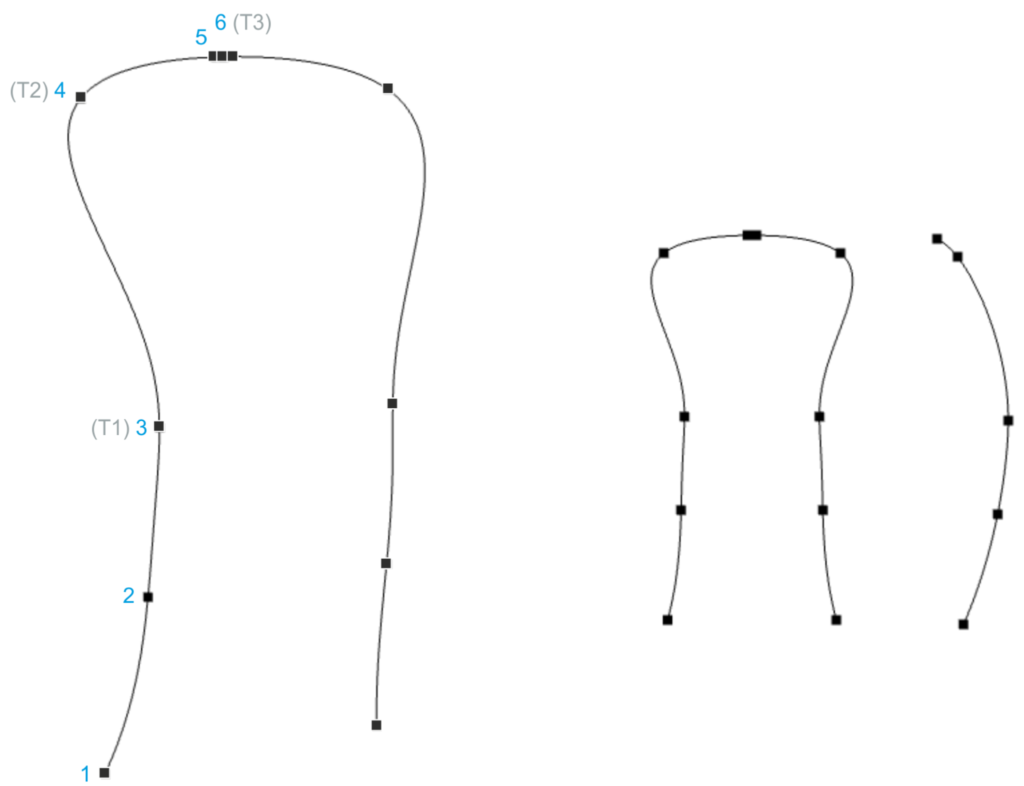
The output information was optimised. In addition to representations of individual components, the list of parameters contains information on the length of the wood rods that will be bent into curvilinear shapes.

6.3.3. General Implementation Procedures

In the following description, the organisation follows the logic designed in SG2, which proceeds in bottom-up and left-right fashion. Points and segments which derive from the shape grammar are indicated. ' and s express projected and symmetry instances, respectively.

The outer frame body comprises five geometrical sets which generate solid representations suitable for other steps in the design process. The geometrical sets are NURBS points, NURBS, adaptive sweep, floor cut and holes.

NURBS points comprise points, instances and planes that support NURBS definition (Figure 96). These sets are directly related to the curvilinear interpretation of the shape grammar points T1, T2 and T3 (Figure 94). Adaptive sweep describes the outer frame variable surface, which is controlled by a law curve (Aish, 2005, p. 13). The two last sets in this geometrical body relate to construction details. The first cuts the bottom of the surface and the latter produces the holes for the seat frame fixture.



POINTS	TANGENT DIRECTION	TENSION	PROJECTED
1	———	——	No
2	———	——	No
3	Z-axis	1	No
4	———	——	No
5	———	——	No
6	———	——	No

Figure 96. Outer frame NURBS definition

The explicit parameters OF_back_height, OF_diameter, OF_back_angle, OF_rear_leg_angle and SF_height allow for dimensional customisation. Shape grammar point variation is set according to OF_rt_back_width_T2, OF_rt_back_height_T2 and OF_rt_waist_width_T1, which control the configuration aspect of the outer frame.

The seat frame is the main aggregator for the remaining chair components. The outer frame is attached to the seat frame. Woven cane or laminated veneer (plywood sheet) is fitted to the seat frame to support the user. The legs are plugged into the seat frame and secured by corner blocks. Only the inner frame and leg brace are not connected to this component.

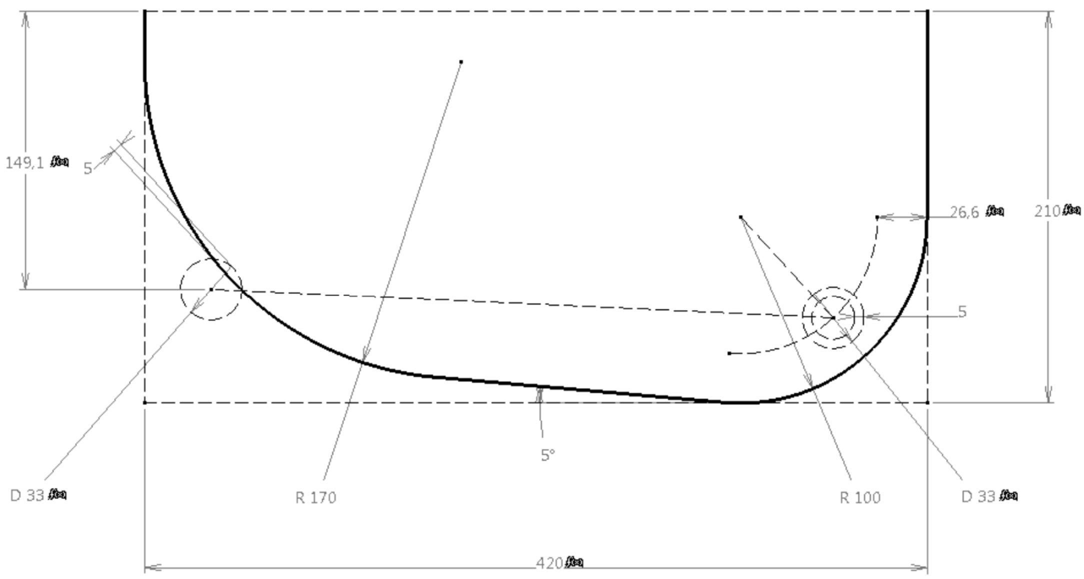


Figure 97. Seat frame reusable sketch

PM2 fully expresses the seat construction principles. A reusable sketch (Figure 97) acts as a reconfiguration schema, describing the topological relationships between all the seat-related components. The trapezoidal reconfiguration is set according to a fixed composition schema parameterised as a function of a rectangle, thereby providing customisation solutions without error.

The seat frame comprises three geometrical sets and additional features required to obtain the final configuration. The surface is swept along the reusable seat guide sketch and a profile. The seat frame profile contains a 15 mm groove to allow pre-woven cane or plywood sheet to be fitted (Figure 98). Additional sets and features establish the holes and grooves required for attaching other components.

The corner blocks and seat cover are defined by reusing the seat guide sketch. Similarly, legs are extruded from the same sketch, with additional properties to describe the tenon and the tapered shape.

In the order of construction for the Thonet chair (Jackson et al., 2003, p. 53), the inner frame is fitted to the outer frame, which is then bolted to the seat frame. The PM2 specification tree does not express this order because in the geometrical model the inner frame definition is completed by using the seat frame geometry.

Since PM2 encodes a direct curvilinear interpretation of the shape grammar rationale, a new strategy was developed to model the geometry of the inner frame. This strategy adopted a modular approach to simplify the implementation procedure for additional topological versions generated by the shape grammar.

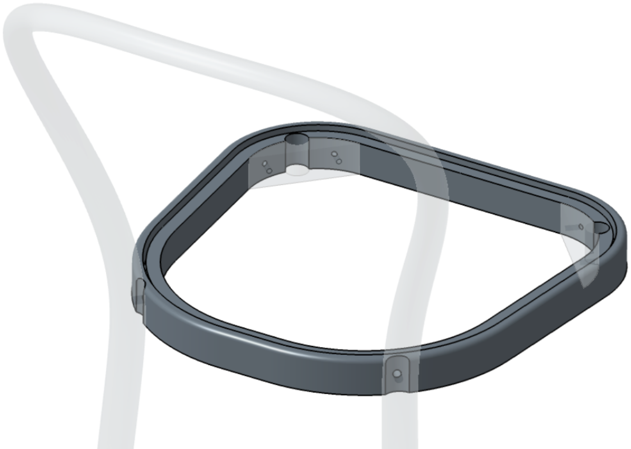


Figure 98. Seat frame, perspective view

The shape grammar solutions are defined by points and segments that connect to the outer frame, the seat frame and the symmetry axis. This condition is implemented in PM2 by a connecting surface between the outer frame and the seat frame (Figure 99). This surface becomes the geometrical space for shape grammar points and segments. The surface description comprises auxiliary geometrical features to separate the shape grammar labels into distinct parts of the outer frame NURBS and to express the adjacency between the chair components. Segments b, c, and d are a function of parameter backrest height. Segment a is directly defined on the seat frame. The transition surface between the top and side areas and the segment a is an interpretation, since it is not described by the shape grammar.

This general model is then instantiated. Each topological version generated by the shape grammar is encoded by connecting a NURBS through the respective points and sweeping it along the respective parameterised surface.

Figure 99. Overview of chair structure

6.3.3.1. Customised Variants from Different Topological Versions

The implementation procedures facilitated the encoding of an additional number of solutions. Moreover, it was possible to extend the exploration of the solution space to other seating typologies, such as counter chairs and canapés (Figure 100).

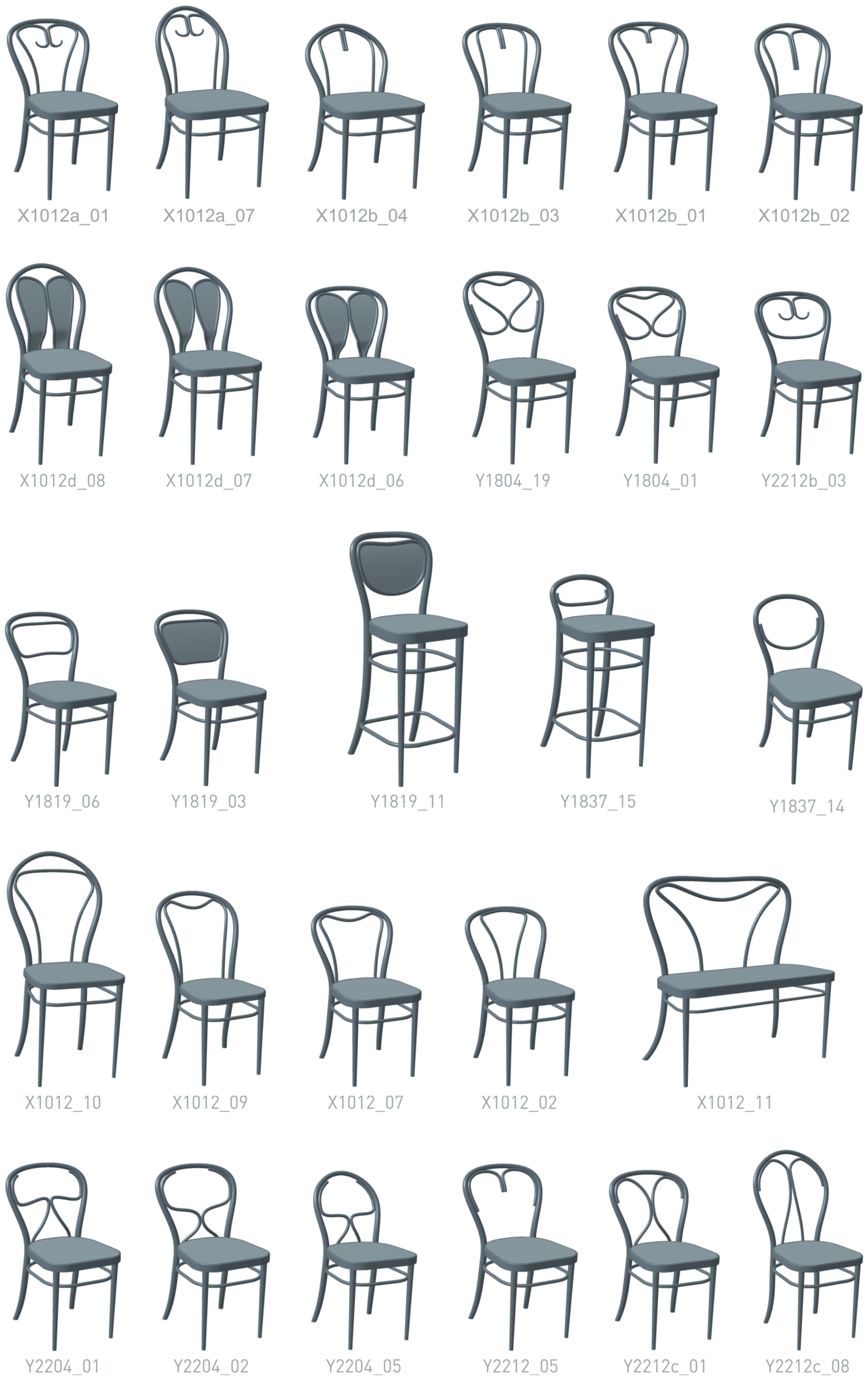


Figure 100. Customised variants created by exploring different parametric design models

6.3.4. The Limits of the Language

PARAMETERS	standard	minimum		maximum	
SF_height (mm)	**460**	400	E	510 / 750	E
SF_width (mm)	**420**	370	Tc	510 / 1100	Tc
SF_depth (mm)	**420**	370	Tc	520	Tc
SF_thickness (mm)	**40**	35	S	60	S
OF_diameter (mm)	**32**	30	M	45	M
OF_width (mm)	**400**	370	S	490	Tc
OF_rt_back_width_T1 (%)	**25**	15	S	40	S
OF_back_height (mm)	**420**	200	S	710	Tc
OF_rt_back_height_T2 (%)	**85**	50	S	100	S
OF_back_angle (deg)	**10**	0	E	20	E
OF_rear_leg_angle (deg)	**7**	5	S	12	S
IF_diameter (mm)	**20**	20	M	35	S

Criteria:
Tc – Thonet catalogue; **E** – Ergonomics; **S** – Style; **M** – Material

Table 10. The limits of the language

Parametric design models provide a wide solution space, which is larger than that of the design language itself. The definition of boundaries for the language, i.e. the lower and upper bounds for the parameters' values, had not been addressed in the development of the first parametric model (PM1). In the transformation of PM1 into PM2, these boundaries were established, following an analysis of information from three sources: the generative design system, Thonet company catalogues, and ergonomics literature. The first came from the results of the shape evaluation subsystem, which provided information on the proportional relations between components and values required to ensure structural compliance. Moreover, in the optimisation tests setup, the variation space for parameters had to be defined, constituting the first assessment of the boundaries or limits of the language. The second source of information was created by the Thonet companies[34]. Analysis of the Thonet 1904 Catalogue and contemporary Thonet companies' websites provided a better understanding of the evolution of the language over time and minor differences amongst designs produced in different regions. The third source of information was ergonomic recommendations for chair design.

Table 10 shows the values for a standard Thonet chair and the lower and upper boundaries for each parameter, i.e. the variation limits for the language.

The seat frame height values were set according to ergonomic recommendations from the literature. The maximum dimension includes a value for the generation of a counter chair, such as the one designed by the Thonet company in Australia (Thonet Australia, 2014). The values for

[34] "Companies" in the plural, since after World War I the original Gebrüder Thonet was divided into various companies, several of which are still operating in different countries today.

the seat frame width and depth were defined after analysing Thonet's 1904 Catalogue. The seat width allows for the generation of canapés. The seat frame thickness values relate to both material and style conformance.

The outer frame diameter values take material considerations into account. The outer frame width was set according to style conformance and Thonet's 1904 Catalogue, while the T1 width variation space conforms to style criteria.

The backrest height minimum value allows for the generation of Thonet stools, a configuration that did not exist but might be suitable for counter stools. The corresponding maximum value was set according to Thonet's 1904 Catalogue. The T2 variation is set according to style considerations.

The backrest angle and leg angle variations respect ergonomic and style criteria, respectively. The inner frame diameter variation is set according to material constraints and style conformance.

6.3.5. Comparison of Parametric Design Models

A comparison of PM1 and PM2 synthesises the extent of the transformation, showing how different interpretations of the shape grammar rationale influence parametric definition.

PM1 comprised an almost direct transcription of shape grammar rectilinear representation into the parametric rationale. As a consequence, sets of procedures were elaborated to obtain the final position of the relevant points in space so that they could control the curvilinear representation. Although some sets of procedures were similar across the different shape grammar interpretations, each parametric design model comprised a different structure. PM1 made it possible to test whether the rectilinear representation considered in the shape grammar was suitable as a guiding structure for the parametric design models. It was shown that it is possible to encode parametric design models comprising rectilinear structures controlling curvilinear representation.

The PM1 representation was modelled in a single geometrical body. Although this type of structure facilitates the implementation procedures and suits the customisation goals, it is not consistent with the fabrication requirements. Since the components have direct implications on each other, particularly in terms of equations and geometrical relations, the extraction of information per component leads to inconsistencies in the overall model.

The PM2 implementation took the PM1 experience as its starting point, providing a well-established base for improvement. The concurrent development of early tests for fabrication also offered a unique overview of the design process, which led to a specific goal-oriented strategy.

PM2 includes direct curvilinear interpretation of the shape grammar rationale, as well as a detailed geometric description of each chair component. Since the information is more detailed, the encoding of the parametric design models required the definition of additional relationships. The difference in the number of parameters between the two models was so great that it ranged from an average of thirty-five equations in PM1 to an average of one hundred and seventy in PM2. The modular approach reduced the complexity of the information and made it more manageable, since geometrical entities and equations could be reused. The type of strategy employed therefore saved time on the development of the parametric design models. The definition of a backrest surface in which all possible points were represented enabled a master parametric design model to be established. Instances of this model were completed with the respective grammar-based topological version, allowing for faster encoding of different designs.

Whereas the outer frame was the central element for parametric structure definition in PM1, in PM2 it was the seat frame. This change in structure was a direct consequence of the level of detail. It reflects the fact that the seat frame is the central element to which almost all the other components are attached.

The encoding of the trapezoidal seat enabled canapés to be generated, which were not part of the initial scope of the study.

PM2 comprises the separation of components based on different geometrical bodies. This condition facilitates both the reconfiguration process for mass customisation and the extraction of information to the production system. The inclusion of component lengths as output parameters enabled a bill of materials for mass customisation to be included and tested.

6.3.6. Discussion

The parametric design models from both implementations facilitated the interactive exploration of grammar-based customised variants. However, their structures are quite different and reflected the particular stage of the generative design system modelling in which they were developed. The PM1 implementation aimed to provide a suitable exploration of shape grammar solutions permitting customisation. PM2 combines these goals with production requirements. The advantage of transforming parametric design models rather than developing them anew is that the previous development serves as a direct benchmark. This premise is different from Hudson's recommendation for parametric modelling (2010, p. 239), which states that early models should be disposable.

During the development of each PM the early 'disposable models' were created to better define the implementation strategy in order to test relationships between parameters and their usability in design exploration. The transformation determined that there were two sets of functional parametric design models for the same solution. Having two sets of functional parametric design models enables each to be analysed in detail and an iterative refinement process to be created. During the PM2 implementation, many of the choices derived from the experience of encoding and using PM1. The modular auxiliary procedures in PM2 are an optimisation of the ones used to obtain the final position of geometrical entities in PM1. The refinement was bidirectional: when PM2 became fully functional, some of its features provided the basis for the refinement of PM1. In particular, it led to the refinement of some equations and curvature definitions in order to achieve better aesthetic conformance.

The use of parametric design models in the digital design process supports the designer in the search for custom solutions. Feature-based modelling has proved suitable for defining parametric relations. Nevertheless, the limitations of current CAD software lead to some difficulties in the encoding procedures. From the experience of encoding and using parametric design models, the author agrees with Sheikholeslami's argument that "current computer-aided design systems provide only the most rudimentary tools for generating, storing and visualizing alternatives" (2010, p. 275).

Nevertheless, parametric design models suit the goals of modelling the backend functionality of a generative design system for mass customisation. The final goal of the generative design system is for this to be translated into a frontend application that can be used by an end user.

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6.4. Optimisation

6.4.1. Introduction

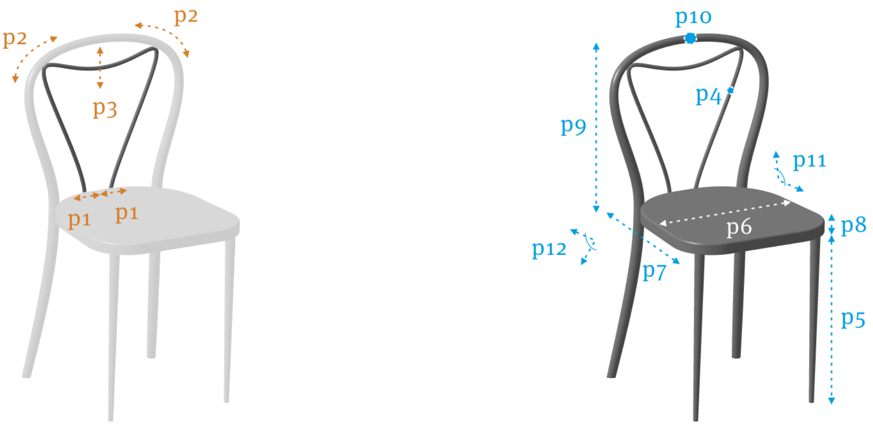
The transformation of the optimisation part follows reflection on the role of evaluation in shape grammars. In order to model the shape grammar and its appropriate evaluation mechanism, several conditions must be assessed. First, the features of the design language that will be subjected to evaluation must be selected. This condition influences the type of algorithm to be used. The encoding of the algorithm for the search requires a decision on the type of representation of the designs which, in turn, is related to other aspects of the design process, namely: 1) the computer implementation; 2) the step of the design where it is introduced; and 3) the integration with other tools used in subsequent steps or phases.

This section details the transformation of the optimisation part, taking as input the transformation of parametric design models and the respective simulation. The goal is the same as the first optimisation encoding (Section 5.5), namely the automated search for an optimal solution that ensures the minimum thickness of the beech wood profiles. This premise follows the explicit goal of guaranteeing compliance of each customised variant with the ISO standards, and the implicit goal of achieving the visual elegance present in the original design style. The transformation aims to closely link the parameters of the shape grammar labels within the search space, a condition not included in the previous formulation. Since the method is similar to the one presented in Section 5.5, this section details the specific modelling aspects of the problem formulation.

6.4.2. Problem Formulation

The goal of optimisation is to minimise equivalent stress to a target value of 18 MPa, which corresponds to a safety factor of 15% below the resistance limit. The respective objective function of the problem formulation is expressed as:

$$\max(\sigma_{\mathrm{eq\,i}}) \sim 18\mathrm{MPa}$$



p1 . Ratio of P1
p2 . Ratio of P2
p3 . Ratio of P3

p4 . Inner frame diameter
p5 . Seat frame height
p6 . Seat frame width
p7 . Seat frame depth
p8 . Seat frame thickness
p9 . Outer frame backrest height
p10 . Outer frame diameter
p11 . Outer frame backrest angle
p12 . Outer frame rear leg angle

Figure 101. Parameters considered in the generation of customised variants, divided into two groups: one controlled by the shape grammar labels (p1-p3) and another only controlled by the parametric models (p4-p12)

Parameters		Parameters values for the initial variant	Lower bound	Upper bound	Increment
p1	Ratio of P1	50 %	0 %	100 %	1 %
p2	Ratio of P2	20 %	0 %	100 %	1 %
p3	Ratio of P3	60 %	0 %	100 %	1 %
p4	Inner frame diameter	10 mm	10 mm	30 mm	1 mm
p5	Seat frame height	450 mm	450 mm	480 mm	1 mm
p6	Seat frame width	420 mm	420 mm	510 mm	1 mm
p7	Seat frame depth	420 mm	420 mm	510 mm	1 mm
p8	Seat frame thickness	30 mm	30 mm	60 mm	1 mm
p9	Outer frame backrest height	420 mm	420 mm	530 mm	1 mm
p10	Outer frame diameter	27 mm	27 mm	40 mm	1 mm
p11	Outer frame backrest angle	0 deg	0 deg	11 deg	1 deg
p12	Outer frame rear leg angle	4 deg	4 deg	10 deg	1 deg

Table 11. Parameters considered in the generation of customised variants, values of the initial variant, range of variation of each parameter, and increments of values used in the search

The range of values of the parameters manipulated by the simulated annealing algorithm in the search for an optimal solution are listed in Table 11. These parameters are used to design a customised variant, and can be divided in two groups (Figure 101). The first group of parameters (p1–p3) comprises the parameters associated with the shape grammar labels used in the generation of the topological version, which can be explored in the parametric design models that encode the grammar to customise the chosen topological version. The grammar defines the variation space, which is explored by the simulated annealing algorithm in the search for the optimal topological configuration of the inner frame. The second group (p4–p12) is related to the configuration of the remaining generic frame, common to all Thonet chairs. These parameters permit the customisation of the aspects not described by the shape grammar, such as the height, width, and angle of the backrest, seat frame, rear legs and front legs. The definition of the range for the optimisation follows the same method defined in Section 5.5.2.

Two sets of tests were performed a priori to formulate in an adequate manner the problem of minimising the equivalent stress to a safety factor, the goal of the optimisation part. The purpose was to gain understanding regarding the most appropriate modelling strategy for optimising Thonet chairs, so that the optimised chair remained closer to the one initially defined by the designer. In the first set of tests all parameters were optimised. In the second set of tests, the parameters associated with the shape grammar labels were not optimised. This second approach was intended to respect the topology selected by the designer using the previous parts of the generative design system.

The same customised variant, using variables values corresponding to the lower bounds, was submitted to the two sets of tests. The compressive yield strength parallel to grain for the 'lower bound chair' or 'initial variant' was calculated as 36.7 MPa, 73% above the yield limit. The initial variant was submitted to optimisation experiments with different available convergence speeds, with time setups of 25, 100 and 400 min established as termination criteria.

6.4.3. Analysis of Results

6.4.3.1. Optimisation of the Complete Chair

Across the tests configured with a slow convergence speed, the same optimised chair was achieved in the 6th iteration (Table 12; Figure 102). When visually compared with the initial variant, the optimised one displays a greater backrest angle. The total of nine parameters, common to all Thonet chairs, was optimised. The backrest angle varied 10º and the backrest height 15 mm from the initial variant. The remaining parameters varied within a range of 5 mm. Out of the three parameters related with the shape grammar's labels, two were optimised: the ratio of P2 decreased 1%; and the ratio of P3 increased 10%.

Tests configured with medium convergence speed yielded two configurations of optimised chairs. In the 25-min and 400-min tests, the convergence was achieved in the 49th iteration. The

100-min test generated the same chair created in the set configured with slow convergence speed.

The visual comparison between the two chairs reveals that the optimised chair from the 49th iteration is closer to the initial variant. The analysis of the numerical results confirm the visual correlation: of the nine parameters common to all Thonet chairs, only five were optimised. Apart from the inner frame diameter, which increased 7 mm, the remaining parameters varied between 1 mm and 2 mm. Furthermore, the proportion between the inner frame diameter and the outer frame diameter was 0.61 (against 0.5 achieved in the 6th-iteration chair), which is closer to the 0.65 proportion verified in the original Thonet design style. Out of the set of grammar-related parameters, two were optimised. Nevertheless, they are very similar to the initial configuration.

A	B	C	D	Value of Optimised Parameters												E
				p1	*p2*	*p3*	*p4*	*p5*	*p6*	*p7*	*p8*	*p9*	*p10*	*p11*	*p12*	
Slow	25	32	6	50	19	70	15	452	423	424	33	435	30	10	7	18.02
	100	428	6	50	19	70	15	452	423	424	33	435	30	10	7	18.02
	400	569	6	50	19	70	15	452	423	424	33	435	30	10	7	18.02
Medium	25	125	49	58	20	58	17	420	420	421	32	421	28	0	4	18.02
	100	139	6	50	19	70	15	452	423	424	33	435	30	10	7	18.02
	400	2138	49	58	20	58	17	420	420	421	32	421	28	0	4	18.02
Fast	25	125	49	58	20	58	17	420	420	421	32	421	28	0	4	18.02
	100	226	6	50	19	70	15	452	423	424	33	435	30	10	7	18.02
	400	569	6	50	19	70	15	452	423	424	33	435	30	10	7	18.02
Infinite	25	98	26	55	24	66	11	450	421	422	30	427	30	2	7	17.95
	100	459	397	53	24	63	12	451	520	422	30	426	30	2	4	17.99
	400	1927	397	53	24	63	12	451	520	422	30	426	30	2	4	17.99

A – Type of convergence speed
B – Time (minutes)
C – Number of iterations
D – Iteration of convergence
E – Stress Value (MPa)

Table 12. Results of the optimisation of the complete chair, sought in the first set of tests

The set of tests with a faster convergence speed produced two optimised chairs equal to the ones created in the medium convergence speed tests. In the 25-min test, the optimal chair was achieved in the 49th iteration, matching the one achieved in the 25-min and 400-min tests configured with medium convergence speed. In the other time configurations, the chair was optimised in the 6th iteration, and it is equivalent to the one created in the 100-min test configured with medium convergence speed.

■ Initial variant ■ Optimised chair [Slow 25/100/400 min; Medium 100 min; Fast 100/400 min. 6th iteration]

■ Initial variant ■ Optimised chair [Medium 25 min/400 min. 49th iteration]

■ Initial variant ■ Optimised chair [Infinite 25 min. 26th iteration]

■ Initial variant ■ Optimised chair [Infinite 100 min/400 min. 397th iteration]

Figure 102. Optimised chair that resulted from the first set of tests, which sought the optimisation of the complete chair, overlaid on the initial variant

The set of tests configured with infinite convergence speed produced two novel optimised chairs: one in the 25-min test and another in both the 100-min and the 400-min tests. Visually, the optimised chairs are very similar. The distinct feature is the rear leg angle, which is greater in the optimised chair in the 25-min test. The analysis of the numerical values for the parameters confirm the similarity between the nine parameters related with the generic frame of the chairs, which vary between 1 mm or 2 mm from the ones used in the initial variant.

In a visual comparison between the four optimised chairs in this set of tests, it is observable that the chair generated in the 49th iteration of the 25-min test configured with medium convergence speed is closer to the initial variant. The variation of the inner frame diameter and of the parameters that control the shape grammar's labels is key to the generation of an optimal chair that is more similar to the initial variant.

A visual comparison of the four optimised chairs in this set of tests reveals that the chair generated in the 49th iteration of the 25-min test configured at medium convergence speed is closest to the initial chair. The variation in the inner frame diameter and the parameters that control the shape grammar labels is the key to generating the optimal chair that is closest to the initial chair.

6.4.3.2. Optimisation of the Generic Frame of Thonet Chairs

The optimisation of the generic frame common to all Thonet chairs also yielded four different chairs across the twelve tests (Table 13; Figure 103).

In the tests configured with slow and medium convergence speed, the same optimised chair was generated in the 30th iteration. From the nine available parameters, seven were optimised, and they differ between 1 mm and 8 mm from the ones used in the initial variant.

In the tests configured with fast convergence speed there were two results: in the 25- and 400-min tests, the optimised chair was the same as the one described in the previous tests. In the chair generated in the 100-min test only three parameters were optimised. This optimal chair is closer to the initial variant, particularly due to the smaller variation of the rear leg angle and to the absence of change in the backrest height.

A	B	C	D	Value of Optimised Parameters (mm)									E
				p4	*p5*	*p6*	*p7*	*p8*	*p9*	*p10*	*p11*	*p12*	
Slow	25	115	30	11	451	420	421	30	428	32	5	9	18.03
	100	142	30	11	451	420	421	30	428	32	5	9	18.03
	400	684	30	11	451	420	421	30	428	32	5	9	18.03
Medium	25	113	30	11	451	420	421	30	428	32	5	9	18.03
	100	484	30	11	451	420	421	30	428	32	5	9	18.03
	400	687	30	11	451	420	421	30	428	32	5	9	18.03
Fast	25	116	30	11	451	420	421	30	428	32	5	9	18.03
	100	496	249	10	450	420	420	30	420	33	5	6	18.02
	400	1984	30	11	451	420	421	30	428	32	5	9	18.03
Infinite	25	107	53	11	456	420	421	32	421	33	4	9	17.99
	100	148	53	11	456	420	421	32	421	33	4	9	17.99
	400	641	98	10	452	421	420	31	425	32	3	4	17.99

A – Type of convergence speed
B – Time (minutes)
C – Number of iterations
D – Iteration of convergence
E – Stress Value (MPa)

Table 13. Results of the optimisation of the generic frame of Thonet chairs only, sought in the second set of tests.

The infinite speed tests generated two novel chairs when compared with the remaining tests in this set. The 25- and 100-min tests produced the same chair as in the 53rd iteration. The chair optimised in the 400-min test was closer to the initial variant, since the rear leg angle was not optimised.

Figure 103 shows the initial variant superimposed on the optimised chairs obtained after the tests. The ones considered closest in terms of similarity are the optimised chair created in the 100-min test configured at fast convergence speed (second row) and the optimised one achieved in the 400-min test configured at infinite convergence speed (fourth row). The 400-min test generated a chair closer to the initial variant. This is observable in the sideways view by the minor deflection in the backrest-rear leg component, which is the direct combination of the backrest angle and rear leg angle parameters.

Figure 103. Optimised chairs that resulted from the second set of tests, which sought the optimisation of the generic frame of Thonet chairs only, overlaid on the initial variant

6.4.4. Discussion

Two problem formulations were submitted to stochastic optimisation of a detailed model of a custom Thonet chair, which is the result of the customisation process enabled by the manipulation of the shape generation subsystem. In the set of tests performed in the first problem formulation, all the parameters were considered in the optimisation; whereas in the second one, only parameters associated with the generic frame were taken into account. Eight optimal chairs were produced in the two sets of tests. In each set, a chair was selected as the best response, considering the dual goal of minimising stress and remaining closer to the designer's original intent. The comparison between these two chairs offers insights about the adequacy of the two strategies used to model the optimisation problem. In the first set of tests, the 49th-iteration chair (Figure 102, second row), which was generated in three tests, was closer to the initial variant. In the second set of tests, this premise was satisfied by the chair generated in the 400-minute test configured with infinite convergence speed (Figure 103, fourth row). A comparison between these two chairs reveals that the complete optimisation of the chair performed in the first set of tests was closer to the initial variant. The ratio between the inner and outer frame diameters is closer to the one in the original design style and the deflection created by the backrest angle and the rear leg angle is less pronounced. This suggests that the first modelling strategy, in which all the parameters are optimised, is more appropriate given the original goal of remaining faithful to the style, despite permitting a change of the original selected topology.

The optimisation presented in this Section suits the goals behind the development of the generative design system. It permits the optimisation of a customised chair according to a safety factor of 15% below the resistance limit, which guarantees that it can perform under operating conditions. Therefore, the system is able to generate structurally sound customised designs.

The use of a stochastic optimisation technique determines that there is a range of optimal designs for both problem formulations instead of only one single solution. The analysis of the results offer valuable insights about the impact of each parameter on the overall design of the chair as a structure, and the particular parameters codified by the shape grammar's labels. Results from this analysis can be used to refine the generative design system before full automation and integration between generation and evaluation is sought. Results can also be used to guide the transformation of the language as explained below.

Regarding the refinement of the generative design system, it may be sought to broaden or restrict the space of possible solutions, thereby increasing or decreasing optimisation time. Such a control of the solution space can be done in the parametric design models by editing the relationships between parameters; in the optimisation setup by changing the ranges of values of the parameters, or even by freezing some parameters to narrow down search; or by editing the simulated annealing algorithm.

Additional transformation of the generative system can be pursued to create novel design languages based on the existing one, following the theoretical premises defined by Knight (1981). As mentioned in Section 2.2.2.7, the combined use of evaluation and shape grammars falls into two categories, syntactic and semantic. Accordingly, shape grammar transformations relying on evaluation and shape grammars to generate appropriate or optimal designs can fall into the same categories.

Syntactic transformation could include topological transformations. In this scenario, Thonet's shape grammar would have to foresee additional topological relations, in which case labels should be unrestricted to amplify the domain of possible solutions. Since labels in the current version of the grammar guarantee functional rigidity, unrestricting them could lead to backrest designs without a proper degree of rigidity. Shape annealing (Shea & Cagan, 1999) would then verify syntactic correctness while searching for structurally optimal designs.

Semantic transformation could follow the methodology of coupling shape grammars with genetic algorithms (Lee & Tang, 2004). In such a case, the Thonet shape grammar would be changed to enable a greater number of design solutions. The solutions output by the optimisation approach presented in this Section could be used as individuals in the development of the genetic algorithm to guarantee structural feasibility. The user would then be part of the search process by ranking the population of individuals output by the genetic algorithm according to his or her preferences. The search for the fittest solutions would then be undertaken taking into account user preferences in the selection of individuals for the next generation, and then the genetic algorithm would be run again. The user's subjective preferences constitute the semantic property of the genetic algorithm. If such subjective preferences can be made explicit and codified into the fitness function, the process can also be fully automated.

The relation between shape grammars and evaluation depends on the amount of knowledge that one is willing or able to put in each of them, the particular step of the design process where they are introduced, and the tools involved.

In the generative design system proposed in this case study, the shape grammar comprises an intrinsic property – the labels – that restricts the domain of solutions. This strategy accounts for a greater fidelity towards the original Thonet design style at the expense of suppressing more novel solutions. It serves the purpose of showing the process of encoding an existing design style into a generative design system for mass customisation, and permits verification against existing knowledge. Evaluation is applied on a different level of abstraction than the one on which the shape grammar operates, and in a subsequent step of the design process. It optimises the preliminary layout into a definitive layout and generates the information for the detail design and production phases. The optimisation addresses structural performance issues in a detailed model, searching for an optimal solution closer to the customised design initially configured by the designer.

The proposed methodology enables the modelling of a generative design system with different complementary parts for generation, exploration, simulation, and evaluation to explore a considerably wide range of feasible designs. These parts can be refined locally or the system can be transformed globally, in order to achieve the desired level of balance between the number of novel designs, the amount of control, and the fidelity towards the original design style.

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6.5. Summary of the Chapter

This chapter presented the transformation of the generative design system, addressing two critical aspects of the establishment and reuse of a product family architecture: product evolution and process iteration.

The generative design system (Chapter 5) encodes a customisable design language, capable of generating several feasible designs, as the technological model of a product family architecture. The transformation of the shape grammar (Section 6.2.) addresses product evolution, by opening up the set of solutions generated by the established design language. The transformation is both incremental, which means that it adds elements to the previous implementation, and iterative, which means that it refines the previous implementation. The experiments demonstrated how internal and external sources of information constitute a solid base for improvement. More particularly, the experiments showed how the systematisation of the initial shape grammar development into a visual diagram can support the transformation of the design language, thereby permitting a product language to be evolved. As a consequence, the transformation of a local part of the generative design system, the shape grammar, enabled the transformation to propagate through the system.

Accordingly, the parametric design models were transformed (Section 6.3.) and accommodated the results from the transformed shape grammar. The methodology for the transformation of the parametric design models also relied on the assessment of the previously encoded information and external sources. The transformation enabled the formulation of a new interpretation of the representation in which the shape grammar operates. In addition, it improved the previous implementation by introducing new layers of information which should be useful in the design process for mass customisation, such as cross-reference naming between shape grammars and parametric design models for better tracking of information; bill-of-materials to know the exact amount of material that is going to be used in production; and the facilitation of the extraction of information for production per component. Furthermore, the transformation permitted an extension of the initial chair typology to generate counter chairs and canapés, thus demonstrating paths for continuous use of the established product family architecture.

In the shape evaluation subsystem, the simulation part accommodated the new results generated by using the previous parts of the system. The transformation focused on the optimisation part (Section 6.4.), by including the shape grammar's labels within the search space. The results from the experiments showed that, despite the fact that it becomes possible an alteration of the chosen topology, the resulting optimised chairs are closer to the ones initially customised by the designer using the other parts of the generative design system. The experiment improved the previous formulation.

The transformation of the generative design system assessed the robustness of the proposed system whilst achieving a new level of balance between the number of novel designs, the amount of control, and the fidelity towards the original design style.

7. The Production System

7.1. Introduction

In product family architecture methodology, the definition of a physical model follows on from the technological model. The solution produced by the technological model constitutes the input information for the physical model. The physical model corresponds to the detail design and production phases, i.e. "that part of the design process which completes the embodiment of technical products with final instructions about the shapes, forms, dimensions and surface properties of all individual components, the definitive selection of materials, and a final scrutiny of the production methods, operating procedures and costs" (Pahl et al., 2007, p. 436). The goal of the physical model is the development of the production system, i.e. the specification and allocation of the fabrication, assembly and product delivery processes.

The generative design system for mass customisation must comprise a connection to a production system in order to ensure that the customised chairs are produced according to the previously defined specifications. As mentioned in previous chapters, Thonet chair components are produced by solid wood bending processes. According to Section 2.4, this type of problem is categorised under forming production systems, more specifically under reconfigurable tooling.

In order to develop a production system capable of assisting the forming process for Thonet chair components, research must encompass the following variables: development of the forming devices and a study of bending procedures, as well as the pre-processing and post-processing of wood. These conditions establish the boundaries for the current research. Experimentation with all the variables would require collaboration with other areas of expertise and access to specific machinery, tools and conditioned environments outside the scope of product design knowledge. However, the initial steps towards future work in this area are conceptualised in this chapter.

The principles for the development of an automated system for the production of bentwood components are defined after a thorough assessment of the specific conditions of the case study and the state of the art in wood bending presented in Section 2.4. With regard to the two types of treatment to plasticise wood – thermo-hydro treatments and chemical treatments – the concepts presented in this chapter are categorised under the first type, more specifically the steam heating method, following the principles defined by Thonet in the 19th century.

7.1.1. The Bending Methods for Thonet Chair Components

The generic structure of the Thonet chair comprises the following bentwood components: the back-rear leg unit (outer frame), the back insert (inner frame), the seat frame, the leg brace and the front legs[35]. The first two require compound bending and the remaining three are produced by planar bending.

Planar bending can be suitable to customisation. Custom moulds can be produced by CNC machining and used to form the seat frame, the front legs and the leg braces. A reconfigurable bending system can be designed to enable these components to be produced to meet the goals of mass customisation. However, the most important elements of the Thonet design language require compound bending. This is observable in the generative design system, which starts with an analysis of the backrest structure – the outer and inner frame – since its design is considered essential to the definition of the Thonet design language. The conceptualisation of the production system therefore focuses on this area, particularly the outer frame.

	Requirements
Goal	Production of the same shape.
Pre-processing	Plasticisation of wood in retorts.
Auxiliary apparatus	Steel strap clamped to both ends of the rod (strap-and-stop).
Moulding device	Fixed shape mould.
Procedures	Manual procedures. Two-cycle compound bending operation.
Post-processing	Wood is loaded in the drying chamber attached to the mould.

Table 14. Requirements for the mass production of the Thonet chair outer frame

Table 14 summarises the original production system developed by Thonet. The transposition of such principles to mass customisation requirements should consider which variables can be changed. As the goal is to use similar thermo-hydro treatments, only the moulding device properties and manual operations are subjected to improvement.

The concepts outlined for the reconfigurable bending system aim to develop a set of general principles and procedures that can be automated. They are based on an analysis of the production of Thonet chairs and the recommendations in the literature for the development of reconfigurable tooling systems (Section 2.4.). The development of concepts follows two premises: the first is the transformation of a continuous moulding device surface into discrete elements; the second is the definition of automated operating principles.

[35] According to contemporary specifications, the front legs of official Thonet chairs produced by Thonet GmbH are not bent. However, the ones produced by TON (Czech Republic) and by Gebrüder Thonet Vienna GmbH (Austria) are still bent.

The concepts described in the following sections imply the pre-processing of wood in retorts, the use of strap-and-stop during the bending operations, and post-processing in drying chambers.

7.2. First Production Concept

The first production concept aims to test the following conditions: the connection between the generative design system and the production system; and the reduction of the continuous surface of the moulding device. Regarding the first condition, the development of this production system makes it possible to test how information is extracted from the generative design system and the steps that are required to produce the moulding device. The reduction of the continuous surface is based on an analysis of existing moulding devices and procedures. The existing adjustable fixtures for planar bending (Fortune, 1985; Jackson et al., 2003 [1989], p. 252), and an analysis of the compound bending method used by Thonet companies (Section 4.2) made it possible to map the possibilities for the development of a moulding device capable of producing custom components.

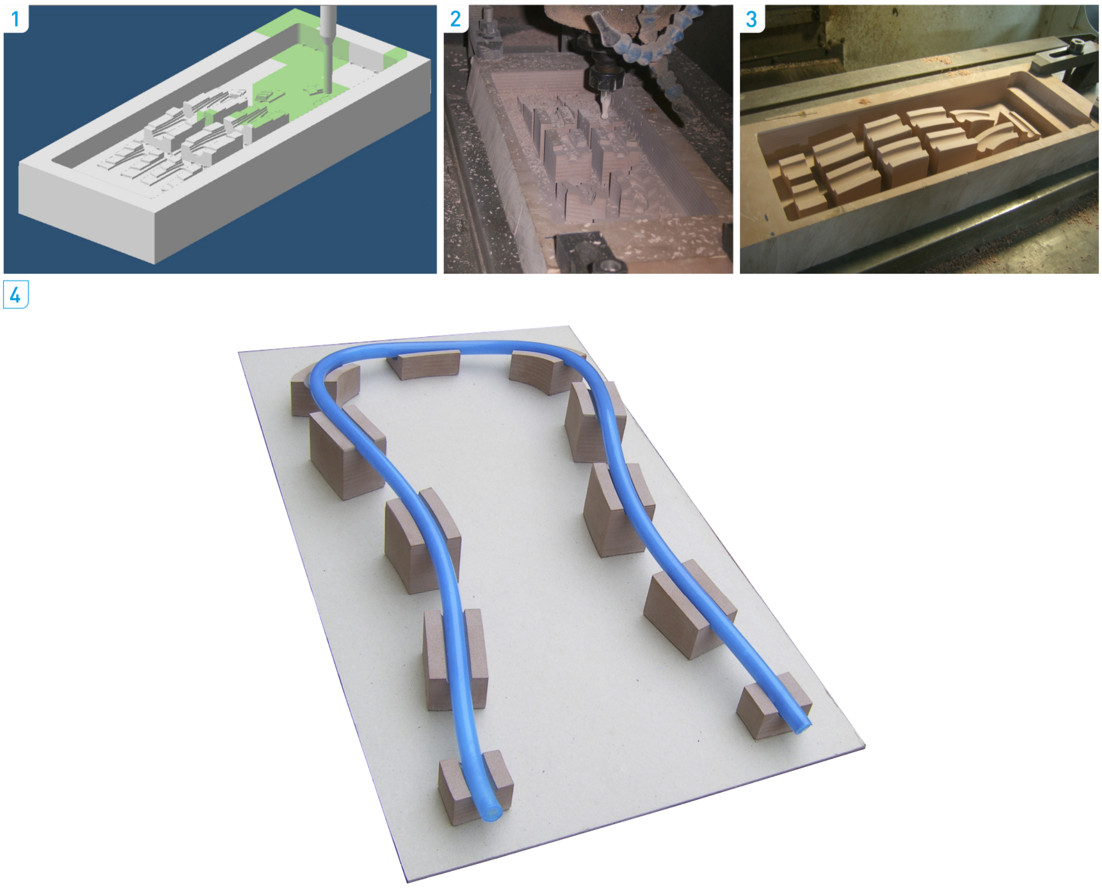

Figure 104. First production concept: steps in the production of the 1/2 scale model

The developed moulding device to bend the outer frame is a set of eleven blocks and a horizontal grid surface for fixture (Figure 104). The bending procedure is meant to be carried out by two workers. The position of each of the eleven blocks emulates the location of the eleven clamps used in the contemporary production method at the Thonet GmbH (Thompson, 2007, p. 200).

The connection between the generative design system and this type of moulding device and its production was tested by the CNC milling of 1/2 scale models. This procedure enabled the intermediary activities that establish the connection between the generative design system and the envisaged production system to be tested. These activities can be classified as three steps: a) encoding additional features in the generative design system; b) post-processing the custom blocks; c) production of the custom blocks.

In the generative design system, the information on the eleven blocks is encoded in the parametric design models. The position of the eleven custom blocks is parameterised in the outer frame, as a function of its length. Additional features complete the procedure for generating the geometry of the blocks. A custom chair is then created using the generative design system, thus informing the position of each of the eleven blocks.

The post-processing of the blocks requires nesting, a procedure which involves laying them out to be produced using the minimum amount of material. Production is then simulated using CAM (Figure 104-1) and the G-code is generated. The production is performed by using a three-axis CNC to mill a piece made out of composite material. Since the eleven blocks were not meant to be used in real bending procedures, there was no additional drilling to create the features for clamping and fitting into the horizontal grid surface.

The envisaged bending operation would make use of similar existing procedures. The bending procedure would be carried out by fastening the eleven custom blocks to the horizontal grid surface. The wooden rod would then be positioned and clamped onto the block in the top area of the backrest. The procedures would then follow the sequence of activities described in Section 4.2.1. After completing the bending operation, the whole structure would be placed in a drying chamber.

7.2.1. Critical Assessment

Although the proposed production concept was not tested, a critical assessment of the envisaged process enabled possible paths for improvement to be estimated.

The representation of the eleven blocks in the parametric design models is encoded in a similar way to the remaining chair components or the apparatus for simulating the ISO tests. It is reconfigured automatically whenever a customised variant is updated in the respective parametric design model.

Regarding the production and use of the moulding device – the eleven blocks and the horizontal grid surface – the procedures should be simpler. The eleven blocks serve a unique customised solution, which means that a set of blocks is produced for each chair solution. Moreover, the geometry of the blocks is different (five pairs plus a single one), and each require additional drilling to create a set of fixtures. These activities are not sustainable in industrial applications due to the amount of work involved in preparing a set of custom blocks that cannot be reused to produce a different customised variant. In this production concept, only the horizontal grid surface is reusable in subsequent bending operations.

Although the production of unique designs is a principle that falls within the goals of the generative design system, it is not the main driver of mass customisation. In fact, production systems for mass customisation require machines with an intrinsic degree of flexibility that enable a range of different designs to be produced. This capacity must be built into the specific machine, similarly than in existing subtractive and additive processes.

The production of a different design requires a different CAM program to generate the specific tool path and may require a change of tools in the machine. Transposing these principles to forming production systems, it is possible to conceptualise a reconfigurable tooling system capable of producing different designs within an envelope of similar solutions.

7.3. Second Production Concept

The second production concept is based on the critical assessment of the first concept. It aims to optimise some of the conditions verified and to emulate the larger set of operations performed during the bending operation. Regarding the reuse of the custom blocks, attempts are made to develop a reconfigurable bending system that does not require a different CAM program for milling blocks for each customised variant. Considering the purpose of industrial application, a solution is presented that supports the future development of automated reconfigurable bending systems.

The result is a production concept that offers two types of manual use. The first involves using a predefined configuration, which resembles the previous concept. The second type attempts to replicate the movements that the wooden rod is submitted to during the bending operation, in order to permit future automation.

The production concept is a machine tool consisting of a fixed table, two rotating panels and eleven sets of modular gripping devices (Figure 105). The table serves as a support for the remaining apparatus. The two rotating panels establish the open position for loading a straight rod and rotate 90º to achieve the end cycle position of the bending operation (Figure 105;

Figure 107). The modular gripping devices enable the wooden rod to be attached and its position to be changed (Figure 106).

The table comprises a pattern of holes to enable one gripping module to be attached in several positions and a pair of pivots to rotate the panels.

Each panel has three larger holes. These holes enable the panel to be rotated on the table pivots. The choice of three possible holes allows for different spacing to accommodate different outer frame widths. Each panel also features a regular pattern of smaller radii holes for adjusting the position of the modular gripping devices.

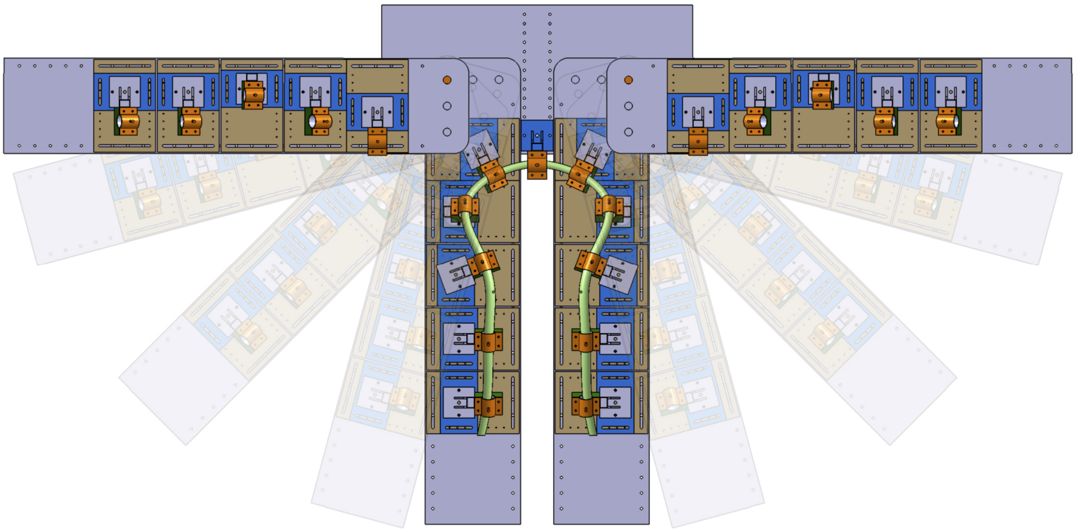

Figure 105. Second production concept

The modular gripping device is a set of elements that allow for the changing movements required to form the wooden rod during the bending operation. Each module has six components (excluding the fasteners): a bottom plate, a base plate, a column and the gripping set. Assuming the module is mounted on the panel in the open position, the bottom plate allows for adjustments on the X-axis and the base plate for the positioning on the Y-axis. The column rotates around the Z-axis.

The gripping set can be raised, lowered or tilted. The position is locked when it is bolted to the column. In addition to the connecting element, there are also two detachable components. These components secure the wooden rod and ensure it is attached to the machine during the bending operation. When the bending is complete, they enable the bent rod to be unplugged from the machine and then post-processed in a drying chamber.

The detachable components are completed with additional elements. Before the bending operation, rubber interpolators should be used to guarantee a tight fit and to prevent any defect in the wood's surface that could lead to failure. After the bending operation, metallic straps should be fastened to secure the bent position.

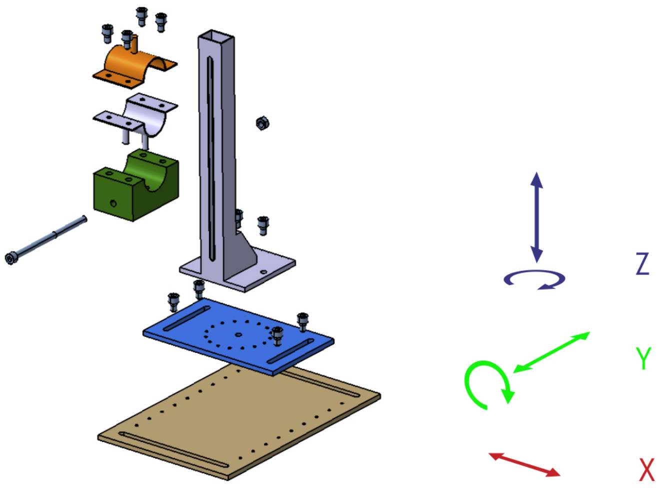

Figure 106. Modular gripping device

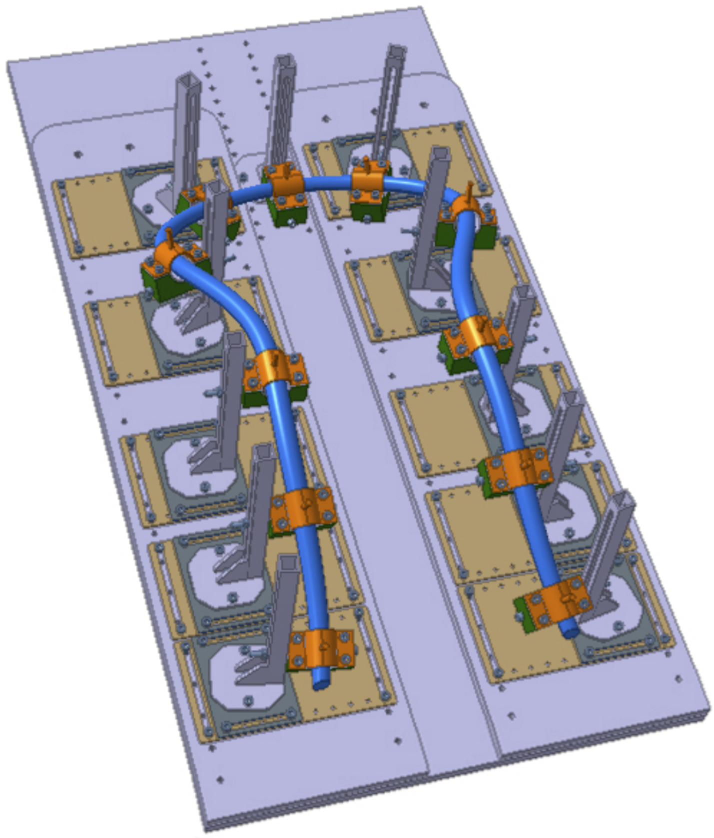

Figure 107. Overview of the complete bending cycle

7.4. Discussion

The concept of a production system as a sequence of the generative design system improves the information developed in the early steps of the design process. The development of the experiments presented here required additional features to be modelled in the parametric design models. This procedure supported their refinement and subsequent transformation (Section 6.3). The representation of the elements for the production process in the parametric design models is a similar activity to the one which prepares them for simulation. The models become the central repository for digital information created during the establishment of the generative design system. They comprise the conceptual structure created from the shape grammar and generate information for the subsequent steps of the design process, including the detail design and production phases in which the production process is established.

In addition to creating the connection between the generative design system and the production system, the experiments also enabled some principles of reconfigurable bending systems to be assessed. Both concepts propose discrete components. The first used custom blocks, which may be suitable for the production of short or unique designs, but does not seem appropriate for the 'mass' production of 'customised' designs[36].

The second concept improved this potential drawback by employing a modular strategy. The detachable components of the gripping set can be available in the diameter range permitted by the design language, thereby simplifying the production process of different customised variants. The remaining components of the machine can be produced in larger batches. These principles minimise the amount of material used in the production of custom chairs since all components can be reused.

With regard to the aim of developing an automated production system for wood bending, the formulation developed in the second concept allows for a critical assessment of the steps to be taken in future work. This concept translates movements that can be replicated by automated machinery. However, certain crucial movements in the implementation of an automatic system were not formulated in the previous presentation and require further explanation.

The bending operation of the outer frame can be summarised in two cycles (Section 4.2.1). The first involves a gentle curve that follows the characteristics of single plane bending. The second cycle is the bend and twist of the wood to achieve the change of plane direction. In automated production, the twisting of the wood would involve the coordinated rotation of the gripping devices. Given that each wooden rod has unique characteristics, a scanning system would be required to automate the twisting function. Scanning would provide information in real time on the torque required to rotate each gripping device.

[36] This expression follows the definition of mass customisation proposed by Stan Davis (p. x) in the foreword of the book "Mass customization: the new frontier in business competition" (Pine, 1993).

Regarding the development of production systems for mass customisation, the experimentation presented here enabled specific conditions to be assessed. The development of reconfigurable forming systems for mass customisation shares some similarities, in the initial steps, with the definition of mass production systems, following the principle that, in both cases, the manufacturing system is specified in advance and guided by design requirements. However, whereas in mass production the manufacturing system is optimised to produce a unique shape, in mass customisation it must include change as a crucial variable. This is related to the definition of the design language and the space required for future improvement. A production system for mass customisation must accept the values established for the design language (Section 6.3.4) as the input information. However, it must also provide space for the additional transformation of the language. For instance, the designs generated by Rule 34 from the transformation grammar (Section 6.2.3) enable the grammar, and therefore the solution space, to be expanded. Accordingly, the possibility for further expansion must be included in the formulation of future developments of the production system. This must involve a trade-off between the possibility of expanding the solution space and the technical feasibility required to accomplish this. Since the concepts for the production system were not tested, it is not possible to assess how the reverse condition may influence the language. Although the bending procedures established the initial boundary conditions for the definition of the language, testing the production system would generate further information for this purpose.

A multidisciplinary team should carry out the future testing and refinement of the proposed concepts in order to gain a better understanding of the possibilities for further development. The testing and establishment of the production system for customised chairs will enable the generative design system to be refined. This is crucial to completing the envisaged model for mass customisation in the furniture design industry and its industrial application.

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7.5. Summary of the Chapter

This chapter presented the conceptualisation of the production system as the physical model of the product family architecture. Since the production system takes as input the digital information created by the generative design system, the conceptualisation followed two major requirements: testing of the encoded digital information and the establishment of the principles for a reconfigurable tooling system for bending solid wood.

The conceptualisation enabled a refinement of the information encoded in the generative design system and the establishment of the means for transforming the generative design system.

Regarding the second requirement, the conceptualisation of the reconfigurable tooling system followed an analysis of the original bending methods defined by Michael Thonet (Sections 2.4.2. and 4.2.1.) and the recommendations in the state of the art for the development of this class of production systems (Section 2.4.1.). As a consequence, two production concepts were presented and discussed, thereby characterising the steps to evolve existing production methods into automated ones capable of enabling mass customisation.

8. Discussion

This chapter reflects on the research developed. The analysis of the case study encompasses three levels: a macro level, a meso level and a micro level. The macro level considers the overall process of the research, which provides an interpretation of the theoretical model (Section 2.5) for mass customisation in the furniture industry. The meso level addresses the development and iteration of the generative design system. In addition, it addresses questions related to the conceptualisation of the production system. The micro level discusses the procedures, methods and techniques developed during the implementation of the generative design system.

8.1. Macro Level

This research takes the paradigm of the post-industrial society as its starting point and the transformation of the economic structure from manufacturing to service-based production. This transformation can be analysed in terms of the constituent industrial models: mass production, lean production and mass customisation. Competitive forces (Porter, 1998, p. 4), such as buyers, suppliers, competitors, substitutes and new companies, foster the transformation from an industrial model to a different type of model.

Mass customisation comprises two major valid strategies: customised standardisation and tailored customisation. Modularity enables the first strategy to be implemented, while digital design provides for the second. The possibilities are greater since the design process, production process and contact with consumers all remain in the same medium.

This thesis proposes a shape grammar-based methodology as the basis for implementing a tailored customisation strategy for mass customisation. The case study focuses on backend operations. Therefore, in order to be serviceable it requires conditions that are beyond the scope of this research. In particular, it requires developing a frontend application to allow for customisation by the consumer. In addition, the complete production system must include the logistics and address the demands of customer-driven manufacturing and other issues related to the management of customer relations.

It differs from existing models based on digital design due to the fact that the customisation possibilities are designed. This is fundamental to the work of the product designer in mass customisation, whose activities do not focus on designing a unique product, but rather on designing a design language. Aspects of the design language will be the constituent information for the frontend application used by the consumer to customise a solution according to his/her own particular goals. Therefore, in order to define the design language, the product designer must have an understanding of the other variables of the design and production processes. The definition of the design language and its encoding as a generative design system must consider those issues as an integral part of the product development process. The issues can be summarised as belonging to generation, exploration, simulation, optimisation and production. In order to address this in the definition and encoding of the design language, the product design activity must include interdisciplinary knowledge as an intrinsic aspect of its core discipline. This integrative approach to product design broadens the scope of its activity. The goal is to enable a designer or a design team to be able to design products for the purposes of mass customisation. The output of the design process is not one unique solution to be produced in large quantities, but instead a system of solutions designed according to the requirements of function, aesthetics, material, and other design criteria, as if it were a unique product that should, nevertheless, maintain a degree of variation. This degree of variation is the customisation space, which must be formalised, refined and optimised to fulfil criteria relating to function, production, and customisation.

The definition of the preliminary layout is the working step in the design process in which these crucial decisions must be taken, in order to define the final design proposal. This working step follows the principle solution defined in the conceptual design phase (Pahl et al., 2007, p. 160), in which several alternatives to the design problem are developed. It requires decisions to be made about formal properties and composition, which must comply with the requirements of functionality, performance and production. As a consequence, the formalisation of the design during this working step is communicated to the engineering department, which is responsible for testing and optimising the preliminary layout into a definitive layout, together with defining the manufacturing system in the detail design and production phases.

The approach used in this research can be characterised primarily as problem-focused, rather than discipline-focused. The emphasis on the problem enables the design- and engineering-related issues in mass customisation to be tackled as part of a complex subject that should be addressed from an interdisciplinary perspective. This principle enables the associated problems of customisation to be modelled into the different steps of the design process, each focusing on a particular set of problems. The computerised implementation of the information developed in the different steps leads to closer collaboration between the disciplines involved. As a consequence, each discipline must attend to the particular set of problems, the general customisation problem, the implementation of information in the generative design system, and the conceptualisation of the production system. Information can be based on the previous step and must communicate with the following step.

Based on the requirements of the subsequent step or the general goals of the system, the information can be validated, refined or iterated. This means that the generative design system can be improved in modular fashion to achieve the desired result, by refining or transforming a particular part or subsystem. One example of the refinement of a particular part can be characterised as the assessment of the scale models produced by rapid prototyping in order to support the improvement of the parametric design models (Section 5.3). The transformation of the shape grammar (Section 6.2) expanded the number of possible solutions, a condition which influences the whole shape generation subsystem.

The modelling of design problems in this way is likely to improve the product design activity in mass customisation. The formalisation of the product within the generative design system is strengthened by the input from multiple disciplines. The reliability of the generative design system is therefore improved, particularly in terms of its capacity to generate multiple solutions that are part of the language formalised by design requirements. The integrative vision of the implementation strategy for mass customisation is achieved by the connection between the generative design system and the production system. The integration between design, engineering and manufacturing issues, and the reduction of the communication gap between them, enables a design and production process to be established that can support the future inclusion of the user within the overall process for mass customisation in the furniture design industry.

8.2. Meso level

8.2.1. The Design Process

The design process in mass production is compartmentalised into independent sequential steps which can be developed by individuals or teams focusing on specific areas. This separation into steps creates challenges in terms of communication. On an operational level, computer-aided design facilitates collaboration, since the medium in which information is generated and transferred remains the same. Nevertheless, the root of some misconceptions occurs at a higher level, and can be characterised as insufficient assessment of the principles, requirements and type of reasoning involved in the subsequent or the preceding connecting step in the design process. Rigid boundaries between disciplines may be one of the causes, leading to issues in the different steps of the design process.

In terms of communications between the fields of design and engineering, two types of problems can be identified. As an example, insufficient knowledge of production requirements on the part of the design team can lead to the need for significant post-rationalisation in a later step in the design process by the engineering team. Conversely, an inconsistent assessment of design criteria by the engineering team may result in an inappropriate solution disregarding pre-established design principles. These situations may delay the design process or require a substantial redesign of the design solution.

In mass customisation there is an intrinsic need to define the output of the design process as a set of customisable solutions. When considering the redefinition of a mass production design process to fit mass customisation requirements, there is a new layer of complexity to the issue of communication or, in other words, the specification of multiple design solutions. The specifications must be precise in order to create an agile design and manufacturing processes.

Accommodating these questions within the design process requires closer collaboration between design and engineering. The former can be summarised as focusing on empirical knowledge, the socio-cultural narratives and the formalisation of such threads within a product that meets the users' needs. Engineering can be summarised as the field responsible for testing the preliminary layout in order to ensure the intended behaviour under specific operating conditions, thus specifying a definitive layout.

These activities occur in the embodiment design phase. Subsequently, in the detail design and production phases, the production process is defined for the definitive layout. Throughout the design process information is exchanged about the product, which means that there is a progressive specification of the product. This exchange of information may create spaces for interpreting the decisions made in the different steps of the design process, which may lead to misconceptions. However, if the product specifications are consistent across the different steps of the design process, it should be possible to map the requirements and decisions, thereby improving the overall process. For instance, it should be possible to relate particular information about a product feature to the step in which it was defined or modified. This type of approach favours the implementation of a robust process for mass customisation, since it allows for the rapid reconfiguration of products, the mapping of potential inconsistencies and closer links between the different disciplines involved in the design process.

Encoding these issues into a generative design system that can be linked to a production system is likely to improve the implementation of a tailored customisation strategy for the furniture design industry. Since the issues are resolved, tested and implemented, they can be translated into a frontend application that allows for contact between consumer and manufacturer. In this scenario, the consumer can customise a solution that can then be produced on demand and delivered.

8.2.2. Shape Grammars

The shape grammar formalises the underlying principles of the design language. The input information is the tacit knowledge developed in the previous steps of the design process. However, in this research an existing design style was used for validation purposes (Section 2.5).

The formalisation of tacit knowledge into explicit knowledge by means of a shape grammar enables both an analytical and a generative definition of a design language to be established. Moreover, this type of formalisation is amenable to computer implementation.

Since there is an interpretation space between tacit knowledge and explicit knowledge, the degree of influence between the two steps can be adjusted. To illustrate this premise, the following scenario, in which the Thonet shape grammar is developed in an earlier step of the design process, may be considered. In the Thonet case study, shape grammars explained the chair-back design, including the range for the topological variation space derived from functional requirements related to chair stability. If the formalism had been employed in the conceptual design phase when the design language was still being developed, the removal of labels would allow for additional design exploration. This type of approach would reverse the design proposal and direct it to more ambiguous realms. It may be useful in cases where the aim is to consider the search for alternative solutions before the embodiment design, detail design and production phases.

Considering the state of the art in shape grammars, two types of exploration can be envisaged for the Thonet shape grammar. The first considers an upstream vertical integration with generic grammars. The second is the possibility of creating a more generic grammar by studying other grammars which characterise different design styles.

The first type of exploration can be conceptualised by coupling the existing type of shape grammar to generic grammars (Beirão et al., 2011) which describe design languages on higher levels of abstraction. Preliminary experimentation involved coupling the Thonet shape grammar with a more generic grammar for chair design developed by Garcia and Romão (2015). There are indications that it is possible to define a generative procedure by means of shape grammars with different levels of abstraction and different layers of rule application. In this case, the generic grammar supports exploration in the conceptual design phase, while the Thonet shape grammar allows for design exploration within a predefined style.

The second conceptualisation follows the conclusions established by Benrós et al. (2012). The authors analysed three shape grammars, each characterising a design style. They then developed a higher abstraction grammar capable of generating solutions belonging to the three different design styles. The methodology involved defining the generic grammar using a subdivision strategy. Since the Thonet shape grammar and Hepplewhite-style shape grammar both employ the subdivision strategy, it is likely that the methodology defined by Benrós et al. could be applied to chair design.

8.2.3. Parametric Design Models

The first principle claimed for shape grammars, namely the opening up of the solution space by decreasing the application of labels in an earlier step of the design process, can be transferred to parametric design models. The degree of freedom in the parametric design models can be addressed either at sketch definition level or at surface definition level. The relations can be defined according to the expected amount of variation. Early parametric design models may feature a greater degree of freedom for exploration purposes, but those employed as definitive in guiding the generative design system and the link to the production system should follow the indications taken from the case study (Sections 5.3 and 6.3) for reducing errors.

The parametric design models are the central repository of information for the mass customisation generative design system and for the connection to the production system. However, in implementing a mass customisation strategy, the information created in the parametric design models should also be used for the marketing functions of a company. Summarising marketing functions as those which manage the variables relating to consumers, there are two main contexts in which parametric design models can be employed. In the first, the marketing function aims to engage the potential consumer with the company before the shopping experience. The second occurs during the shopping experience.

In the first context, the parametric design models can be used to generate information for communication purposes. Rendered images or three-dimensional augmented reality models can be used for image-based media such as advertising, catalogues, websites or mobile applications.

Regarding the second context, the purchasing scenarios must be envisaged in order to specify the role of parametric design models. According to Gros' virtual production scenarios (Section 2.1.3), there are two possible ways of configuring a custom product: the virtual one, using online configurators, and the physical one, set in product galleries which offer a configuration service and exhibit furniture samples.

Configurators should provide an appropriate user experience. In establishing a frontend application for the generative design system, the inclusion of additional features should be assessed. Additional features can be coupled to the frontend application in order to provide better support, such as an advisory system, during the configuration process. Advisory systems can be an integral property of the generative design system (Duarte, 2001) or can be developed separately for the frontend application (Blecker et al., 2004).

In terms of this research, the frontend application must be developed separately. As it can present a different structure for the end user, additional disclosure is required. The structure of the Thonet parametric design models involves a continuous type of customisation. This means that the geometric variation can be set across all the parameter values, creating a higher degree of customisation than modularity, which is a discrete type of customisation. The type of customisation offered can be assessed through the implementation of the frontend application. This assessment must consider the desired interaction offered to the end user.

Given that the user may be able to choose between an unassisted and an assisted configuration process, the presentation may be different. The unassisted configuration process can be presented as a continuous type of customisation which allows the user to tailor the appearance of the product completely independently. On the other hand, the assisted configuration process can guide the user through a range of discrete sizes, thus simplifying the customisation experience. Nevertheless, this type of discrete customisation is still greater than the one permitted by modularity. The generative design system developed in this research permits both customisation scenarios to be presented.

As product galleries are physical spaces for customisation, they must provide additional information for the user, in comparison to the frontend applications accessed online. In this type of service, parametric design models should help bridge the gap between virtual representation and physical object. The aim is to help the user to make a better assessment of the characteristics of the customised product before the selected customised variant is produced. Accordingly, there are three possible outputs for parametric design models. They can be used to generate rapid prototyping models and virtual reality models from a customised variant selected by the end user. Additionally, they can be used to generate samples of customised variants to be displayed at the product gallery, to provide a better shopping experience for the end user.

8.2.4. Simulation and Optimisation

In the case study, performance-based information formalised in the simulation and optimisation parts of the shape evaluation subsystem expresses structural requirements as the assessment condition. This principle is likely to be used in other situations. The establishment of the shape evaluation subsystem must consider the product's features, user needs and production constraints.

Other formulations in chair design may comprise optimisation to a suitable posture based on a specific user or predetermined function. In such cases, the search algorithm should be refined to include the required data in its properties.

Optimisation problems may also be formulated as multi-optimisation problems. The formulation should involve a thorough assessment of the cross-influence between variables, and their influence in the definition of the overall product. These types of activity imply a different set of skills in design activity, which will be debated in the micro level assessment.

8.2.5. Transformation

Each part of the generative design system was implemented and the results tested in accordance with the specific goals of the part and its connection to the following part. When the generative design system was complete, its capacity was assessed against the goal of generating a design language that could be customisable. The connection between the generative design system and the production system was then tested. The analysis of these activities established the requirements for iteration. The transformation of the shape generation subsystem and the accommodation of the transformation within the shape evaluation subsystem showed that the establishment of a generative design system for mass customisation is an iterative design process.

The transformation of the shape grammar aimed to increase the solution space. A diagram representing the steps involved in the development of the initial shape grammar supported the transformation methodology. The development of the diagram allowed for critical assessment of the decisions made and enabled the mapping of spaces where a change in reasoning occurred. Changes in reasoning can be characterised as the interpretation of tacit knowledge into explicit knowledge (Nonaka, 1994). For instance, the analysis of the material application in existing Thonet chairs is formalised in the algebras W in the shape grammar. The mapping of the steps and decisions made during the development of the shape grammar enabled its transformation strategy to be outlined.

The transformation of the parametric design models aimed to refine the digital information, taking into account the remaining steps in the design process and production process. The test of the connection between the generative design system and the production system determined the refinement of the parametric design models. The refinement activity assesses how the information created by the shape grammar is encoded, how the information generated connects to the shape evaluation subsystem and how it is used in the production system.

The transformation of the shape evaluation subsystem focused on the optimisation part. It addressed the modelling issue of connecting shape grammars and evaluation; and the goal of optimising a design that remains closer to the original intention defined by the designer. The optimisation can be connected to the shape grammar, even though it is applied on a different level of abstraction and in a different step of the design process. In addition, the optimisation of a detailed model allows for the automatic search for a definitive layout in a mass customisation design process.

The type of methodology presented in this research is likely to improve the establishment of design systems for mass customisation, by facilitating the development, testing, refinement and iteration of the encoded information in order to achieve the desired extent of customisation.

8.2.6. Production

Reitman, quoted by Bonsiepe (1992, p. 208), defined the links between the constituent elements of a problem as follows: characterisation of the initial situation, characterisation of the end state, and the process of transformation that occurs between them. A situation can be classified as relatively well-defined (or well-structured) or relatively ill-defined (or ill-structured.) In well-defined situations, the variables are structured beforehand or there is a clear path to guide the solution. In ill-defined situations the variables are open or many of the constraints and criteria are unknown (Cross, 2000, p. 14).

Bonsiepe defined the following four types of combination between the initial situation and the end state, which can be used to classify a design problem:

“1. Well-defined initial situation, ill-defined end state;

2. Well-defined initial situation, well-defined end state;

3. Ill-defined initial situation, ill-defined end state;

4. Ill-defined initial situation, well-defined end state.”

Considering the relationship between the design and the production of Thonet chairs in mass customisation, the problem can be classified as the first type. In other words, at the beginning of the case study the design of Thonet chairs was known, whereas the production system for their customised production was not.

The development of forming production systems for mass customisation comes under the first and third classes of Bonsiepe's taxonomy, since they require the development of dedicated production systems defined by design requirements. The implementation of mass customisation strategies using existing additive or subtractive processes can be characterised under the second and fourth classes.

Forming is the class of manufacturing system most widely used in mass production (Thompson, 2007, p. 11). It is used to manufacture a wide range of materials, from natural composite materials, to synthetic composites and metals. This range of applications across different industries indicates the importance of developing reconfigurable tooling systems for mass customisation. In order to establish forming production systems as efficient alternatives to mass production, it is necessary to overcome issues related to the scale of the components produced, the production cadence, the surface quality of the artefact produced, and the sustainability of the production process.

In this research, this class of production system was studied in relation to the bending of solid wood. The goal was the production of custom shapes created using a generative design system. The conceptualisations presented in this research propose the first steps towards this goal, namely the analysis of manual procedures and its interpretation into sets of automated principles, together with an analysis of the existing subtractive processes used to produce tooling. Future steps should include cooperation with materials science in order to test the variables related to the alteration of material properties during the bending process, and the load-bearing capabilities under operating conditions. In addition, the use of additive processes should be considered in the production of tooling.

8.3. Micro Level

The case study was implemented in CATIA, which is feature-based parametric software with integral of CAD, CAE, and CAM modules. The majority of the procedures were based on techniques that build on the traditional use of CAD tools in product design. These techniques can be implemented directly in other feature-based parametric software. In graph-based software, the equations must be translated into input and output relations in the visual programming interface, in order to guide the reconfiguration of the parametric design models.

Programming languages were not used to encode the information in the CAD, CAE, and CAM procedures. However, programming enables the designer to interact more directly with the foundations of computational design. The set of four parts proposed in the generative design system is based on an algorithmic rationale that is likely to be suitable for implementation using programming languages. Programming could also lead to the improvement of certain procedures. In parametric design models, some tools could be customised and some modular procedures could be codified as recursive functions. In optimisation, for instance, the specific characteristics of the case study could be encoded in the simulated annealing algorithm.

The possibility of including programming as a design method does not mean that the designer's work would overlap with that of the software engineer. The design activities should continue to focus on solving design-related issues aiming at the ultimate goal of defining a valid space for customisation with the purpose of answering users' needs. However, programming skills could help to expand the scope of the generative design methods. This capacity could prove similar to the one afforded by parametric modelling, in comparison with static CAD representation. Nevertheless, the potential increase in the complexity of the design problems and codification procedures may lead to the need to include a third party dedicated to computer implementation.

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9. Conclusion

This chapter presents the conclusions of the research, demonstrating the significance of the work for the areas of knowledge involved: mass customisation, design methods, shape grammars, digital design and furniture design. After an overview of the research, its contributions are listed and paths for future work are proposed.

9.1. Overview of the Research

The thesis proposes an integrated model for mass customisation in the furniture design industry, for the purpose of improving the patterns of collaboration between the fields of design and engineering in defining a customisable design language. The proposed model uses a generative design system and a production system supported by computer-aided design. The ultimate goal is to enable products to be designed that can be customised by individual consumers according to their own idiosyncratic intentions.

The generative design system allows for the generation, exploration and evaluation of custom solutions in four parts, contained in two interconnected subsystems: shape generation and shape evaluation. The design language is encoded in the generative design system according to the rules of form, composition, representation, function and material properties. The conceptualisation of the production system addresses the development of a reconfigurable tooling system for wood bending which directly reflects the requirements of the design process, the specific features of the product, and the constraints of the material.

The theoretical model is illustrated by its application to an iconic mass production problem, namely Thonet bentwood chairs, changing it to comply with the paradigm for mass customisation. The design language is encoded in the shape generation subsystem by a shape grammar which is used by the designer to create alternative design solutions by manipulating rule application. The shape grammar is implemented as a set of parametric design models to allow for the interactive generation of customised variants. The shape evaluation subsystem complements the shape generation subsystem by simulating and optimising the customised chairs to meet structural requirements under operating conditions. These subsystems both formalise the design language and yield information to guide the automated production of customised furniture.

The iteration of the shape generation subsystem readdresses the development of the shape grammar and the parametric design models. The transformation of the shape grammar expands the number of generated solutions. The transformation of the parametric design models simplifies the encoding of the shape grammar, in addition to improving the digital information that is used in the shape evaluation subsystem and the production system. The iteration of the shape evaluation subsystem readdresses the development of the optimisation part, enabling optimal chairs to be generated that remain closest to the original intent of the customised variant.

The model proposed in this thesis allows for the establishment of a design language, the generation of multiple solutions in the language, the transformation of the language to expand the universe of possible solutions, simulation and optimisation under operating conditions to select a feasible custom solution, and the generation of information for the production of custom designs. These conditions are likely to improve the design process for mass customisation in the furniture design industry.

9.2. Contributions

9.2.1. Findings

Design for mass customisation determines that the output of the design and production processes is not a single object, nor a set of modular objects. It is rather a customisable design language which generates feasible designs. Designing within this model involves transformations to the prevailing design methodologies, both at product and process level. The findings from the research presented in this thesis are the following:

The generative structure of the design language becomes explicit when defined by a schematic representation. The simplified depiction of shape properties separates the underlying structure of a design from its geometrical representation. This higher-level schematic representation improves the assessment of the topological relations between components in a design. In addition, it clarifies the relations of similarity established across different designs. These conditions facilitate the definition of the generative procedures.

Curvilinear shapes can be represented by simplified rectilinear equivalents. This principle leads to a simplification of the rules to describe a design style that includes curvilinear shapes.

A shape grammar can be implemented as a set of different parametric design models. Each different topological version generated by applying the rules of a shape grammar can be implemented as a unique parametric design model. This condition allows for the parametric exploration of customised variants in a predefined topology. Furthermore, it enables information to be generated for subsequent steps in the design process and for the production system.

Implementing a shape grammar as parametric design models may involve different internal structures. A shape grammar based on a rectilinear representation to simplify a curvilinear representation can be encoded as parametric design models comprising different internal structures. In the first implementation, the rectilinear representation of the shape grammar is encoded as a direct wireframe structure that guides surface representation. In the second implementation, the parametric design models comprise a curvilinear representation of the shape grammar schema. The direct curvilinear representation simplifies the encoding procedures for the parametric design models.

A feasible design language for mass customisation is gradually formalised in the constituent parts of the generative design system. A design language for mass customisation requires the establishment of a feasible solution space that guarantees the performance of any customised product under operating conditions. This space is gradually formalised in each part of the generative design system. The generative structure, the geometry, the variation space, and the boundaries for the search space based on performance criteria define the feasible solution space for the design language.

A diagrammatic representation of the procedures used to develop a shape grammar facilitates its transformation. The development of such a diagrammatic representation requires an analysis of the procedures undertaken during the development of the shape grammar. It provides information on the constituent elements of tacit knowledge and decomposes the interpretation into explicit knowledge, such as shape grammar properties. The decomposition presents implications on different levels. An example of an implication across levels may inform which features in the corpus of designs are inferred in the grammar. An implication within a level involves the visualisation of which rules generate a greatest number of solutions. This principle permits the designer to estimate possible strategies for the transformation of the shape grammar, by assessing the implications of the decisions at a particular level and/or across levels.

9.2.2. Main Contributions

The main contributions of this thesis are:

1. A theoretical model for a generative design system for mass customisation in the furniture industry.

   The system envisaged requires a frontend application and a production system. The thesis addresses the generative design system, clarifying the formalisation procedures that allow for the definition and customisation of a design language, support for design decisions in the design process, and the preparation of information to guide the production system.

2. The definition and encoding of a design language using a generative design system consisting of four parts.

   The generative design system is organised as a set of successive parts, which enables the user of the system to customise a feasible solution that belongs to a design language by following a series of steps. In addition, the design language can be refined and transformed by working on a specific part or subsystem. The proposed generative design system for mass customisation includes a methodology that takes knowledge from design and engineering into account, both essential to the design process and therefore required for the success of mass customisation.

3. A systematised method to introduce incremental transformation in a shape grammar.

   The diagrammatic representation of the elements analysed, the procedures carried out during the development of a shape grammar, and the properties of the latter enables the extent of the implications to be estimated in advance, thereby allowing the designer to outline and assess the transformation strategy beforehand.

4. A characterisation of the Thonet bentwood chair design style.

   The research provides knowledge on the underlying principles of Thonet bentwood chairs designed in the 19th century. Taking as its starting point a diagnosis that addresses design, construction, and production issues, the study identifies the patterns developed by Thonet that give the bentwood chair design style coherence.

5. An outline of a reconfigurable tooling system for compound wood bending.

   The research defines the principles required to develop the existing production methods for compound wood bending into reconfigurable tooling systems for wood bending. This type of system can automate the wood bending production process, thereby facilitating the mass customisation of bentwood chairs.

9.3. Future Work

The thesis proposes an integrated model for mass customisation in the furniture design industry, which may constitute a paradigm for the whole field of product design. Future work might evolve in two directions. The first concerns overcoming the limitations of the proposed model, whereas the second involves extending the model to enable it to be applied to the product design field in general.

9.3.1. Improvements to the Research

This thesis proposes a method for creating integrated generative design systems that bridge the gap between design, engineering, and manufacturing. In order to produce a fully functioning system, the following issues should be addressed:

1. Development of the production system.

   The conceptualised reconfigurable tooling system for wood bending and the proposed prototypes should be submitted to additional testing and development before full implementation is achieved. The ultimate goal is the automated manufacturing of custom bentwood components.

2. Assessment of the shape evaluation subsystem.

   As a consequence of developing the production system and constructing custom chairs, it will be possible to analyse physical behaviour by means of experimental tests and compare them with simulation performance behaviour. The results of these tests would provide valid information for fine-tuning the properties used in the simulation and the optimisation parts.

3. The development of frontend applications for end users.

   The generative design system proposed in this thesis should include a frontend application to allow for customisation by users, the ultimate goal of mass customisation processes. The development of this frontend application, either a configurator or an innovation toolkit, should consider the type of user support during the customisation procedures, the level of interactivity, and the degree of openness to allowing the user to go beyond *a priori* set limits. In this regard, the hypothesis of the author is that different types of users should have different levels of permission to control the customisation procedures.

9.3.2. Improvements to the Field

The steps towards full implementation of the envisaged model should comprise the following future work:

Use of the grammar-based approach to develop new products. In this thesis the formalism is applied to characterise a specific type of chair and focuses on a specific area. Future work should aim to describe new types of products and new sets of functions. Within the context of new types of products, coupling generic grammars for a wider search for solutions at product level with specific grammars for an in-depth search at component or area levels can also be explored. Regarding new sets of functions, the aim should be to encode in shape grammar properties the intrinsic product functions that consider internal relations between components, and the extrinsic product functions that are related to the interaction between product, user, and context.

Implementation of information to support all phases of the design process. The thesis proposes the development and implementation of information within a generative design system focusing on an interdisciplinary perspective involving design and engineering in the embodiment design phase. Future work should focus on coupling this type of information with information used in other phases, namely exploration that occurs in the conceptual design phase and data related to the manufacturing and assembly definitions that occur in the detail design and production phases. These types of information could also be formalised as libraries in order to facilitate their reuse in the future development of new products.

Development of custom-built integrative software. The implementation of the grammar-based generative design system was achieved by using existing integrated software. Given the requirements of mass customisation, certain limitations were still observed in the integration and reuse of information in the different modules. Future work should consider the development of software with the capacity to achieve the seamless integration of information produced by the different parts of the generative design system.

Definition of multi-objective optimisation problems. The research reduced design to a single optimisation problem by considering one performance design goal only – structural integrity. Future work should consider multi-objective problems, in which variables representing different goals could be combined into a single objective function using weights, according to the degree of influence they have in the overall design of the product.

Study of sustainable reconfigurable tooling systems. Forming is a ubiquitous class of production system employed in mass production. The study of the transformation of forming systems into reconfigurable tooling systems capable of producing customised designs may encourage the adoption of mass customisation as the new production standard.

These recommendations may be valid only if linked to methods aimed at enhancing the customisation experience for the end user. These methods must pursue the design endeavour to create true value by finding the most advantageous intersection points between the goals of the designer, manufacturer and user.