Rapid Manufacturing

An Industrial Revolution for the Digital Age

Editors
N. Hopkinson, R.J.M. Hague and P.M. Dickens
Loughborough University, UK

John Wiley & Sons, Ltd

Rapid Manufacturing

Rapid Manufacturing

An Industrial Revolution for the Digital Age

Editors
N. Hopkinson, R.J.M. Hague and P.M. Dickens
Loughborough University, UK

John Wiley & Sons, Ltd

Telephone (+44) 1243 779777

Email (for orders and customer service enquiries): cs-books@wiley.co.uk
Visit our Home Page on www.wiley.com

Other Wiley Editorial Offices

John Wiley & Sons Inc., 111 River Street, Hoboken, NJ 07030, USA

Jossey-Bass, 989 Market Street, San Francisco, CA 94103-1741, USA

Wiley-VCH Verlag GmbH, Boschstr. 12, D-69469 Weinheim, Germany

John Wiley & Sons Australia Ltd, 42 McDougall Street, Milton, Queensland 4064, Australia

John Wiley & Sons (Asia) Pte Ltd, 2 Clementi Loop #02-01, Jin Xing Distripark, Singapore 129809

John Wiley & Sons Canada Ltd, 22 Worcester Road, Etobicoke, Ontario, Canada M9W 1L1

Wiley also publishes its books in a variety of electronic formats. Some content that appears in print may not be available in electronic books.

Library of Congress Cataloging-in-Publication Data

Rapid manufacturing: an industrial revolution for the digital age/
edited by N. Hopkinson, R.J.M. Hague, and P.M. Dickens.
p. cm.
Includes bibliographical references and index.
ISBN-13 978-0-470-01613-8 (cloth : alk. paper)
ISBN-10 0-470-01613-2 (cloth : alk. paper)
1. Rapid protoyping. 2. Rapid tolling. I. Hopkinson, N. II. Hague, R. J. M. III. Dickens, P. M.
TS171.4.R34 2005
620′.0042′0285–dc22 2005018264

British Library Cataloguing in Publication Data
A catalogue record for this book is available from the British Library

ISBN-13 978-0-470-01613-8
ISBN-10 0-470-01613-2

Typeset in 11/13pt Palatino by Thomson Press (India) Limited, New Delhi, India.
Printed and bound in Great Britain by Antong Rowe Ltd, Chipperham, Wiltshire
This book is printed on acid-free paper responsibly manufactured from sustainable forestry in which at least two trees are planted for each one used for paper production.

Contents

List of Contributors

Dave Bourell Mechanical Engineering, The University of Texas at Austin, 1 University Station Stop C2200, Austin, TX 78712, USA, dbourell@mail.utexas.edu

Ian Campbell Department of Design and Technology, Loughborough University, Loughborough, UK, r.i.campbell@lboro.ac.uk

Phill Dickens Rapid Manufacturing Research Group, Loughborough University, Loughborough, UK, P.Dickens@lboro.ac.uk

Poonjolai Erasenthiren Rapid Manufacturing Research Group, Loughborough University, Loughborough, UK, p.erasenthiren@lboro.ac.uk

Brad Fox Center for Rapid Manufacturing, 11195 Kenora Way, Lakeville, MN 55044, USA, rapidinsert@yahoo.com

Tim Gornet Rapid Prototyping Center, University of Louisville, Louisville, KY 40292, USA, Tim.gornet@louisville.edu

Richard Hague Rapid Manufacturing Research Group, Loughborough University, Loughborough, UK, R.hague@lboro.ac.uk

Russ Harris Rapid Manufacturing Research Group, Loughborough University, Loughborough, UK, r.a.harris@lboro.ac.uk

Neil Hopkinson Rapid Manufacturing Research Group, Loughborough University, Loughborough, UK, n.hopkinson@lboro.ac.uk

Rik Knoppers TNO Science and Industry, Postbus 6235, 5600 HE Eindhoven, The Netherlands, g.knoppers@ind.tno.nl

Janne Kytannen Freedom of Creation, Hobbemakade 85 hs, 1071 XP Amsterdam, The Netherlands, janne@freedomofcreation.com

Fred McBagonluri Siemens, 10 Constitution Avenue, Piscataway, NJ 08844, USA, fmcbagonluri@siemens.com

Martin Masters Siemens, 10 Constitution Avenue, Piscataway, NJ 08844, USA, mmasters@siemens.com

Monica Savalani Rapid Manufacturing Research Group, Loughborough University, Loughborough, UK, m.m.savalani@lboro.ac.uk

Rupert Soar Rapid Manufacturing Research Group, Loughborough University, Loughborough, UK, r.c.soar@lboro.ac.uk

Roger Spielman Technology Development Manager, Solid Concepts, 28231 Avenue Crocker Bldg 10, Valencia, CA 91355, USA, rspielman@solidconcepts.com

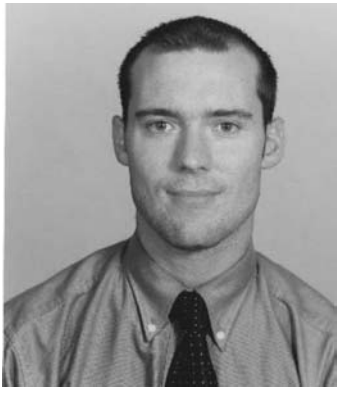
Graham Tromans Rapid Manufacturing Research Group, Loughborough University, Loughborough, UK, G.P.Tromans@lboro.ac.uk

Chris Tuck Rapid Manufacturing Research Group, Loughborough University, Loughborough, UK, c.j.tuck@lboro.ac.uk

Therese Velde Siemens, 10 Constitution Avenue, Piscataway, NJ 08844, USA, tvelde@siemens.com

John Wooten 625F Ivywood Lane, Simi Valley, CA 93065, USA, jrwooten@sbcglobal.net

Editors



Neil Hopkinson is a lecturer in the Wolfson School of Mechanical and Manufacturing Engineering at Loughborough University, UK. Having obtained his PhD in Rapid Tooling in 1999, Neil began to look into the economic viability of Rapid Manufacturing. Inspired by the findings of this research Neil began to investigate low-cost, high-speed Rapid Manufacturing processes while also focusing his research on material properties in powder-based layer manufacturing processes. To date Neil has secured over £1 million of research funding and published over 40 journal/conference papers; he was also an invited visiting lecturer at the University of Queensland in Australia.

Phill Dickens is Professor of Manufacturing Technology and Director of the Innovative Manufacturing and Construction Research Centre at Loughborough University, UK. He is also Associate Dean of Research for the Engineering Faculty. Phill started work in the area of Rapid Prototyping in 1990, working on processes such as 3D Welding and using copper coated SL models as electrodes for EDM. The research work has changed emphasis since then from Rapid Prototyping to Rapid Tooling and is now concentrating on Rapid Manufacturing.

Richard Hague is a Senior Lecturer and Head of the Rapid Manufacturing Research Group at Loughborough University, UK. He has been involved with Rapid Prototyping and Rapid Manufacturing (RM) research since 1993, and is now Principal Investigator on several large EPSRC, DTI and EU funded research projects. He was also instrumental in setting up and managing the successful Rapid Manufacturing Consortium that now operates from Loughborough. Richard has many academic publications in the area of Rapid Manufacturing and is referee to several international academic journals and conferences. He also holds a patent that was gained as part of his PhD studies which is licensed to the predominant manufacturer of Rapid Prototyping equipment (3D Systems Inc.).

Foreword

It is a privilege to write the Foreword for this very important book. Rapid Manufacturing (RM) is the next frontier for researchers, developers and users of a technology that has been used predominately for Rapid Prototyping. The additive, freeform nature of the technology, coupled with improvements in materials, processing speed, accuracy and surface finish, opens up an array of options that before were impossible. In the not too distant future, series production applications of the technology will propel machines sales and the number of parts produced annually to impressive new levels. The numbers for Rapid Prototyping applications will pale in comparison.

RM has a promising future with a powerful list of potential benefits. In fact, a growing number of companies are betting their future on systems for Rapid Manufacturing. The technology makes it feasible to manufacture series production parts economically in quantities of one to several thousand pieces, directly, depending on part size and other factors. Without the constraints imposed by tooling, designers are given the freedom to create new designs that before were impossible or impractical to manufacture. This method of manufacturing presents a dramatically different way of thinking and the future implications are staggering. Personalized products become possible because the cost of producing a unique design is not prohibitively expensive, as it is with tooling or other costly methods of manufacturing such as casting.

True just-in-time manufacturing becomes a reality because companies can produce parts as they are needed, rather than in large batches as they are done today. The relatively simple and automated operation of the machines makes it far easier to decentralize production operations. Placing machines at or near customer sites and sending new designs to them using Internet tools also becomes an interesting option.

Most new designs never see the light of day because they are too risky to manufacture due to the high cost of tooling. When tooling is removed from the equation, it becomes feasible to introduce new products in low quantities to see whether a market demand exists for them. The established method is to spend months, or longer, and hundreds of thousands of euros, or more, to find out whether a new design is a winning product.

Many nations are losing much of their manufacturing base to countries that can produce products much less expensively. RM will help these nations preserve some of their manufacturing because it will become impractical to manufacture low quantities of parts in such far away places. Manufacturing parts locally, and just in time, will become much more attractive than manufacturing them halfway around the world because of the time and cost of shipping. Also, design data that are sensitive will remain inside the company.

The Rapid Manufacturing Research Group at Loughborough University shares this vision. It is the only group of its kind in the world with a staff of academic professionals dedicated exclusively to Rapid Manufacturing. In recent years, the group has expanded to more than 40 researchers who provide a continuous stream of new ideas, new projects and new results. I have had the pleasure of working with and getting to know many of these fine people and I can say without reservation that they are among the top thinkers in the world. They have gained my respect and the respect of countless others.

The Rapid Manufacturing Research Group has secured some of the best people in the industry to contribute their ideas and experience to this book. The collective knowledge and experience of these people has resulted in a publication like no other. Study it, absorb its many ideas and examples, and use the information to form your own opinions about RM's future. Finally, feel fortunate that this group has come together to help advance product development and manufacturing around the world. Congratulations to them for this impressive achievement.

Terry Wohlers
Wohlers Associates, Inc.

1

Introduction to Rapid Manufacturing

Neil Hopkinson, Richard Hague and Phill Dickens
Loughborough University

1.1 Definition of Rapid Manufacturing

The definition of Rapid Manufacturing (RM) can vary greatly depending on whom one talks to. For some people it can simply mean making end-use parts quickly – by any manufacturing method – while for others it involves the use of an additive manufacturing process at some stage in the production chain.

Our definition is very clear and precise. Rapid Manufacturing is defined as 'the use of a computer aided design (CAD)-based automated additive manufacturing process to construct parts that are used directly as finished products or components'. The additive manufactured parts may be post-processed in some way by techniques such as infiltration, bead blasting, painting, plating, etc. The term 'additive' manufacturing is used in preference to 'layer' manufacturing as it is likely that some future RM systems will operate in a multi-axis fashion as opposed to the current layer-wise manufacturing encountered in today's Rapid Prototyping (RP).

Although current RP systems are being successfully used in specialist applications for the production of end-use parts, these RP systems have not been designed for manufacturing and many problems remain to be solved. These include surface finish, accuracy and repeatability, among others. We are currently in a transition stage where RP systems are being used for these specialist, low-volume and customised products but true manufacturing that

Rapid Manufacturing: An Industrial Revolution for the Digital Age
Editors N. Hopkinson, R.J.M. Hague and P.M. Dickens

is of a sufficient speed, cost and quality that can be accepted by the general consumer does not exist at present.

The field of Rapid Manufacturing has grown in recent years and offers such significant potential that it must be considered as a discipline in its own right that is independent from its predecessors of Rapid Prototyping and Rapid Tooling. This new discipline, which eliminates tooling, has profound implications on many aspects of the design, manufacture and sale of new products.

1.2 Latitude of Applications

It is difficult to think of a technological discipline that has such a broad range of potential applications as Rapid Manufacturing. What other technology can get an artist, a medical clinician, an engineer and an environmental champion excited in the same way? This almost unparalleled latitude of applications is reflected in the range of materials that may be processed. We are only in the early stages of developing the technologies but are already able to reliably process parts in polymers, metals and ceramics and the potential for functionally graded components adds a degree of freedom for a combination of materials that had not previously existed. Not only is there a great breadth of potential for Rapid Manufacture, but the discipline also brings about issues of significant depth, uncovering new ways of thinking in terms of many aspects ranging from involvement of the customer in the design process through to the ability to realise new engineering solutions to problems in the aeronautical industry.

1.3 Design Freedom

The design freedoms afforded by Rapid Manufacturing are immense and the processes are capable of creating mind boggling geometries. In the short life of layer additive manufacturing technologies the processes have outstripped the capabilities of CAD, in many cases the bottleneck in producing parts is their design, while making them is the easy part. Prior to the advent of these technologies, has mankind ever been in the situation where visualising and designing a product is actually harder than making it?

As these technologies are more commonly used and their products seen by the general public then the creativity that can make full use of the potential of the processes will be realised. As today's computer literate children grow up they will be able to unleash their creativity in ways that had not been possible before. It is possible that three-dimensional modelling packages will be become standard pieces of software – how long before we see Microsoft

CAD? There will need to be considerable work in the development of such packages to suit the new generation of computer literate but non-engineering specialised designers of tomorrow.

1.4 Economic for Volumes down to One

The elimination of tooling, for products where machining is difficult or impossible, opens up a host of possibilities for low and medium volume Rapid Manufacture. Indeed, the concept of widespread economic manufacture to a volume of one may, for the first time, be facilitated by this technology. This mode of manufacture is likely to involve the customer very closely and will prompt the need to bring manufacturing close to the point of sale – reversing the current drift of manufacturing from west to east.

The issues brought about by widespread manufacture to a volume of one are many and varied. The process of design is likely to require an increased amount of virtual prototyping with all new products subject to design optimisation and testing using finite element analysis. Production and product proving will be changed and certification standards such as CE etc. will need to be reviewed in the light of these new possibilities. Also the legal ramifications will need to be considered; if a customer designs or has a role in designing his or her own product and a product supplier manufactures the product, who will be liable in the event of a product failure?

1.5 Overcoming the Legacy of Rapid Prototyping

In our experience it appears that one of the main stumbling blocks for the increased uptake of Rapid Manufacture is a frequent reticence to accept it as a genuine possibility. For every individual who can see the opportunities that Rapid Manufacturing offers, there is another who prefers to focus on why it can not or will not happen. The latter response is often taken in spite of clear evidence that Rapid Manufacture is already happening.

Rejection of the concept of Rapid Manufacture usually comes in the form of comparison (for example of material properties) with existing processes. The problem at this point is that Rapid Manufacture is seen as merely an extension of Rapid Prototyping and so parts are not seen to be suitable or intended for end use. This 'baggage' of Rapid Prototyping is probably a larger hurdle to the uptake of Rapid Manufacturing than any of the technical issues that we face. Overcoming this viewpoint will take time, more evidence of success and the ability to present the benefits in a clear and balanced way.

1.6 A Disruptive Technology

Many of the issues discussed above are clear symptoms of a technology that can be described as disruptive. Rapid Manufacturing offers profound possibilities across a broad spectrum but has initially been met with a wide-ranging degree of acceptance, often leading to lively debate!

1.7 A Breakdown of the Field of Rapid Manufacturing

Through our extensive involvement with this new discipline we have identified four key areas of the technology and have arranged the chapters of this book to fall within these areas of:

- Design
- Materials and processes
- Management and organisational issues
- Applications

We are intrigued by what we have found as this technology has developed and are excited about the future that it holds. We hope that this book introduces the topic in a manner that does justice to the next industrial revolution.

2

Unlocking the Design Potential of Rapid Manufacturing

Richard Hague
Loughborough University

2.1 Introduction

One of the principal advantages of taking an additive (Rapid Manufacturing) approach to manufacturing over more conventional subtractive or formative methods comes not from manufacturing approach per se but from the dramatic advantages that are possible in the area of *design*. This potential for radically different design methodologies is one of the major drivers for the development of Rapid Manufacturing systems and materials and is a powerful reason why some organisations are able to put up with the sometimes severe limitations associated with current Rapid Prototyping (RP) systems to gain an advantage today.

The main benefit to be gained by taking an additive manufacturing approach (including most, but not all, of the currently available RP techniques) is the ability to manufacture parts of virtually any complexity of geometry entirely without the need for tooling. In conventional manufacturing, there is a direct link between the complexity of a part and its cost. In Rapid Manufacturing (RM), not only is complexity independent of cost but also the RM techniques are able to produce virtually any geometry. If this principal were extended to true manufacturing processes then the opportunities for product design and manufacturing are immense.

Rapid Manufacturing: An Industrial Revolution for the Digital Age
Editors N. Hopkinson, R.J.M. Hague and P.M. Dickens

This need for tooling in conventional manufacturing represents one of the most restrictive factors for today's product development. The absence of tooling within the additive manufacturing processes means that many of the restrictions of 'Design for Manufacture and Assembly' (DFMA) [1] that are essential in a modern manufacturing environment are no longer valid [2]. In injection moulding, for example, the need to consider the extraction of the part from the (usually expensive) tool takes an overriding precedence in the design of the part. Thus the high cost and need for tooling greatly limits product design and compromises have to be made. Without the need for tooling or necessity to consider any form of DFMA, the possibilities for design are literally only limited by imagination.

During the last few decades, designers have been educated to develop designs with restricted geometry so that parts can be made easily. The revolutionary aspect of Rapid Manufacturing will be that geometry will no longer be a limiting factor. Compounding the fact that as high volumes do not need to be manufactured to offset the cost of tooling then the possibilities for affordable, highly complex, custom parts become apparent. In theory, each part that is produced could be a custom part and thus there will be the potential to economically 'manufacture to a unit of one' [3]. The ability to produce whatever geometry that is created in a three-dimensional computer aided design (CAD) system actually means that one is entering a new dimension of 'Manufacture for Design' rather than the more conventional 'Design for Manufacture' philosophy [4].

This freedom of design is one of the most important features of RM and is extremely significant for producing parts of complex or customised geometries, which will result in reducing the lead-time and ultimately the overall manufacturing costs for such items. RM will affect manufacturers and customers alike. For manufacturers, costs will be dramatically reduced as no tooling is required and for customers, complex, individualised products will be cost-effectively made that can be configured to personal use, thus giving the potential for much greater customer satisfaction [5].

Rapid Manufacturing will enable fast, flexible and reconfigurable manufacturing to occur that will have enormous benefits to manufacturers and consumers. The elimination of tooling and the subsequent removal of many DFMA criteria will realise significant benefits in the design, manufacture and distribution of a part or components, including:

- Economic low-volume production
- Increased flexibility and productivity
- Design freedom

The subject of 'Design for Manufacture' is potentially broad. However, this chapter will concentrate on the 'freedom of design' aspects and will give details of specific areas of design that are only enabled by taking an additive approach to manufacturing.

2.2 Potential of Rapid Manufacturing on Design

The main feature of RM processes is the ability to produce parts of virtually any shape complexity without the need for any tooling. The impact of this factor on the validity of guidelines that designers comply with when they are designing for manufacture and assembly are discussed below.

2.2.1 Conventional 'Design for Manufacture' (DFM)

DFM is a philosophy or mind-set in which manufacturing input is used at the earliest stages of design in order to design parts and products that can be produced more easily and more economically. DFM is any aspect of the design process in which the issues involved in manufacturing the designed object are considered explicitly with a view to influencing the design. Some principals are used for efficient manufacturing, such as: developing a modular design, using standard components and designing for multi-use and to be multi-functional. By far the most important principle is to design for ease of manufacture and fabrication, which could be different depending on the manufacturing processes adopted. These guidelines are well documented elsewhere [1,6].

For years, designers have been restricted in what they can produce as they have generally had to design for manufacture – i.e. adjust their design intent to enable the component (or assembly) to be manufactured using a particular process or processes. In addition, if a mould is used to produce an item, there are therefore automatically inherent restrictions to the design imposed at the very beginning.

As the range of plastic products being produced by RP and RM processes are quite comparable with those of injection moulding of plastics, some of the rules necessary for injection moulding are given here in order to provide a basis for the consideration of design rules for Rapid Manufacturing. These include:

1. *Draft angles.* These are important for ease of removal of parts from moulds. The inclusion of draft angles at the design stage is very important, but often omitted.
2. *Minimising re-entrant features.* 'An easy to manufacture part' must be easily ejected from the mould. Designing undercuts requires the use of side cores. This in turn will require moving parts in the dies that add to the tooling costs considerably. Some parts containing features such as blind

holes and galleries are impossible to manufacture without using very complex and expensive tooling arrangements.
3. *Wall thickness consideration.* Components with thin walls solidify faster, hence reducing warpage and production costs.
4. *Uniform wall thickness.* Non-uniform wall thickness will result in compression and expansion of molecules, resulting in compressive and tensile stresses. The stress in turn will result in cracks, crazing or fractures of moulded parts.
5. *Minimising weld lines.* When different flow fronts (due to obstruction within the mould or various gates) meet each other, this creates weld or fusion lines. These are a source of weakness within the part and should be minimised during design.
6. *Avoiding sharp corners.* These will provide tensile, compressive and shear stress on the moulded parts, which in turn will become stress concentration points, leading to part failure.
7. *Ejection pin marks and gate marks.* These could have an adverse aesthetic effect on the injection-moulded part. However, with adequate consideration their impact could be minimised.
8. *Parting line.* The direction of mould closure and parting line is also crucial in tooling and injected parts. Much consideration and deliberation is needed for their selection.
9. *Minimising sink marks.* These are formed when a thin section becomes solid sooner than a developed thicker section. Sink marks could be less apparent by adequate consideration during design.

2.2.2 Conventional Design for Assembly (DFA)

By adopting DFA guidelines at the design stage, significant reductions in manufacturing cost and improvements in the ease of assembly can be achieved [7]. A few of these guidelines are briefly given here [1,6]:

1. *Reducing parts count.* Eliminating unnecessary parts, combining parts or eliminating or reducing the number of fasteners could achieve this.
2. *Reducing handling time.* A few simple, logical and effective rules, such as avoiding tangling and nesting parts or using easy-to-handle symmetrical parts, would result in a more efficient assembly.
3. *Ease of insertion.* This involves designing parts that are easy to align, easy to insert and self-locating with no need to be held in place before insertion of the next part.

2.2.3 Impact of RM on DFM and DFA

As the first RM processes will most probably be plastic processing systems, the most immediate competition will be with injection moulding. RM, unlike injection moulding, is a tool-less process, which does not involve any melting and subsequent solidification of materials within the confines of a tool. Therefore, considerations for constant wall thickness (to aid the flow of material), avoidance of sharp corners and minimising weld lines, sink marks, ejection pins, gates marks and draft angles will no longer need to be considered.

However, the significant impact of RM will be on the guidelines associated with minimising complex geometries and features such as undercuts, blind holes, screws, etc. Incorporating such features in conventional injection moulding is not impossible but often requires expensive tooling, extensive tool set-ups, testing runs and prototyping. This inevitably leads to undesirable lead-times and costs. Also, any simple modification in design requires a new set of tooling. However, as RM is a tool-less process, the part complexity is not important and any complex shapes or features produced by CAD can be directly translated into the final product. This is in marked contrast to conventional manufacturing processes.

Also, in injection moulding, the selection of the correct location for the split line – in particular for asymmetrical and complex-shaped components – is quite difficult and is largely dependent on the experience of the tool designer. However, by adopting RM processes and not using any tooling, designers will be entirely freed from this task.

By using RM technologies, it will be possible to reduce the number of parts within an assembly. Therefore, the most important DFA guideline, which concerns the reduction in part count, is easily achievable. In theory it is possible to reduce the number of parts to just one, though in practice this may not feasible as parts are generally not being used in isolation and their interaction with other components would impose limitations on a part's count.

Thus, with the advent of the Rapid Manufacturing techniques, there is the potential for many of the current obstacles to be removed. The following sections discuss the design freedoms afforded by RM and also deal with some potential problems that are likely to occur with the onset of Rapid Manufacturing in general.

2.3 Geometrical Freedom

As discussed, one of the major benefits of some additive manufacturing processes is that it is possible to make virtually any complexity of geometry at no extra cost. This is virtually unheard of, as in every conventional manufacturing technique there is a direct link from the cost of a component to the complexity of its design. Therefore, for a given volume of component, it is effectively possible to get the geometry (or complexity) for 'free', as the costs incurred for any given additive manufacturing technique are usually determined by the time to build a certain volume of part, which in turn is determined by the orientation that the component is built in.

Areas of particular interest that are enabled by the freedoms afforded by RM include:

- Design complexity/optimisation
- Parts consolidation
- Body-fitting customisation
- Multiple assemblies manufactured as one

These areas are discussed in greater detail in the following sections.

2.3.1 Design Complexity/Optimisation

The design freedoms afforded by RM will enable increasingly complex designs to be realised that are fully optimised for the function that they are required for. Design optimisation is common in the construction industry where optimal structures for bridges and buildings are derived using optimisation techniques and then subsequently fabricated. For example, Figure 2.1 shows the proposed Beijing National Stadium, which has been designed by Arup for the 2008 Olympics. This building has been designed with a combination of design optimisation and genetic algorithms to produce a truly unique structure, but one that is structurally sound.

It is proposed that, due to the freedoms of design afforded by RM, this approach can be used much more extensively for product design – this approach is less common in the product design arena as the optimised design will often prove impossible to make due to DFM criteria. This is one of the main stumbling blocks for so-called Knowledge-Based Engineering (KBE) systems that often have finite element analysis (FEA) as the kernel.

Initial work at Loughborough University has investigated the use of design optimisation to create complex internal structures. Figure 2.2 illustrates a

[Image not available in this electronic edition.]

Figure 2.1 Proposed Beijing National Stadium designed by Arup (8)