The University of Nottingham

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DESIGN FOR MICROASSEMBLY - A METHODOLOGY FOR PRODUCT DESIGN AND PROCESS SELECTION

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Abstract

The thesis presents research carried out in the field of design for microassembly (DFμA), a field that has hereto been characterised by the absence of well defined methodologies intended to facilitate transfer of prototypes from the research lab to production on industrial scale. A DFμA methodology has been developed, serving the purpose of integrating product and microassembly process development. It aims in particular at increasing the efficiency of the microproduct development process, decreasing the development time and the product and process cost, and enhancing the product quality.

Chapter 1 presents the motivations, objectives, and structure of the thesis. The work carried out is inspired by the need to overcome barriers currently existing between the making of single research products and production on an industrial level. The main objective is to contribute to the creating of a novel DFμA that supports product design and process selection, thereby facilitating the efficient assembly of complex three-dimensional miniaturised devices. This is complemented by a range of secondary targets that deal with the development and verification of supporting methods and models related to DFμA.

The summary of a comprehensive literature review is given in chapter 2. The survey provides results of studies closely related to the work reported in this thesis and relates that work to a larger ongoing dialogue about the topic of assembly and design in the microworld.

Chapter 3 outlines the research approach adopted here for the developing of a DFμA methodology. It carefully analyses the way in which the knowledge

gaps identified can be addressed and how the stated objectives can best be achieved.

The key contributions made to the developing of a DFμA methodology are presented in chapters 4, 5, and 6. The microassembly process capability model is described first, in Chapter 4. It constitutes the first attempt made at introducing a general framework for capturing of microassembly characteristics. The model developed enables selection and characterisation of microassembly processes. A framework to characterise the model's application to microjoining, -feeding, and -handling is as well suggested.

Chapter 5 concerns the actual DFμA methodology. The methodology's layout and structure are introduced in detail. Moreover, the main functions and key phases of the methodology are explained. Special attention is paid to the integration of the microassembly process capability model and to the development of further elements used within the methodology, such as support in product design.

Provided in Chapter 6 is a comprehensive analysis of conventional DFA guidelines, intended to explain how the microspecific guidelines have been formulated. The chapter also describes how these are implemented within the overall DFμA methodology.

The procedure of validating and illustrating the methodology, which includes applying it to practical test cases, takes place in Chapter 7. The thesis is concluded in Chapter 8, wherein evidence of the originality of the knowledge contribution achieved through the work presented is highlighted. Opportunities for further research work building on the foundations laid here are outlined in the providing of an overview of upcoming challenges with respect to DFμA.

Acknowledgements

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All the contributions provided to this thesis helped improve the end result. Any remaining weaknesses or errors are of course solely my responsibility.

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List of abbreviations

3DM	3D-Mintegration – The design and manufacture of 3D miniaturised integrated products – An EPSRC Grand challenge research project
AEM	Assembleability evaluation method
ASF	Assembly sequence flowchart
AI	Artificial intelligence
BCIT	British Columbia Information and Technology Branch
CAD	Computer aided design
CMM	Coordinate measurement machine
DFA	Design for assembly
DFμA	Design for microassembly
DFM	Design for manufacturing
DIN	Deutsche Industrienorm: German industrial standard
DOF	Degrees of freedom
EMCC	European Monitoring Centre on Change
EPSRC	Engineering and Physical Sciences Research Council
FDA	Food and Drug Administration
FEM	Finite Element Model
FMEA	Failure mode and effect analysis
GMP	Good manufacturing practices
GUI	Graphical user interface
IC	Integrated circuit
IPR	Intellectual property rights
ISO	International Organisation for Standardisation

KC	Key characteristics
LIGA	Lithography, electroforming, and moulding
MEMS	Microelectro mechanical systems
MINAM	European Technology Platform for Micro- and Nanomanufacturing
MST	Microsystems technology
NIST	National Institute of Standards and Technology
NPL	National Physical Laboratory
OECD	Organisation for Economic Co-operation and Development
OEM	Original equipment manufacturer
OMG	Object Management Group
OOP	Object oriented programming
PDM	Process development model
PI	Physik Instrumente GmbH & Co. KG
PMMA	Polymethylmethacrylate
QFD	Quality function deployment
RIE	Reactive ion etching
SEM	Scanning electron microscope
SMA	Shape memory alloys
SME	Small- and medium -sized enterprises
SRA	Strategic research agenda
STM	Scanning tunnelling microscope
UML	Unified modeling language™
VDI	Verein deutscher Ingenieure e.V.: German Association of Engineers

1 Introduction

Microsystems technology (MST) is considered to be an enormously strong economic driver in the 21st century. The market size for microsystems and microtechnologies is expected to more than double from €8.8 billion in 2005 to €18 billion by the year 2009 (Nexus, 2005). A large volume of products in MST is predicted within the next decade. In this context, *microassembly* shows vast potential in a wide range of industrial MST applications, particularly in the high-tech areas of medical/surgical, automotive and transport, biotechnology, and consumer products. However, at present it is generally acknowledged that this potential has only been shown by the development of demonstrator products within research environments and that it is not yet possible to transfer it to industrial practice (e.g. Popovic, 2004, Alting *et al.*, 2003, Hesselbach and Raatz, 2002).

Microassembly is of particular importance in the production of multi-material devices with complex and true three-dimensional geometries. It is characterised by part dimensions from sub-millimetres to a few millimetres with functional part features in the range of micrometers, small tolerances, and high positioning accuracy, typically 0.1-10 micrometers (Tichem *et al.*, 2004). The worldwide trend of miniaturisation of products has led to assembly challenges which need to be solved to compete in today's fast-moving global marketplace.

Conventional pick and place techniques as well as other microelectro mechanical systems (MEMS) driven developments are not sufficient because of their limitations to planar configurations and non-complex geometries. Likewise it is not possible to simply downscale conventional macroassembly technologies since handling parts which measure only micrometers in diameter needs to consider several difficulties which do not occur at the macroscale. Moreover, sticking effects are caused by surface tension, electrostatic and van der Waals forces. Some microparts are extremely fragile and sensitive to contamination, which means that special manipulation and feeding techniques as well as clean room environments become necessary.

To deal with the high complexity of the products and processes in the microdomain a *design for microassembly* (DFμA) methodology is here introduced with the aim of facilitating the efficient assembly of complex three-dimensional miniaturised devices. Currently neither the literature nor any of the common Design for Assembly (DFA) tools provide sufficient solutions for the microworld.

1.1 Motivational background

In general it can be stated that launching innovative products on the market is one of the most important strategic success factors of any company or as NIEBEL AND DRAPER are quoted to have said in 1974:

> *"The life blood of any individual product-producing enterprise is the continual introduction of new products" (Niebel and Draper, 1974).*

These new products must address potential customer needs or demands, and sustain pressure from competition. There are additional difficulties due to globalisation and technological advancement. On the one hand, the products' innovation cycles become shorter, which in turn means that the available time for product development decreases. On the other hand, the products' complexity increases dramatically due to a range of different functions and technologies from diverse areas including mechanics, electronics, and computer science (Eversheim and Schuh, 2005).

Consequently, companies have to address the challenge of developing innovative products in a minimised period of time in order to secure their long-term competitiveness. Fundamental for successful product design and market launch is an effective and efficient product development process (Cooper, 2002). *Effective* means choosing the right innovations whereas *efficient* means reaching the developed product (output) with the least resource input.

It is well recognised that the production of miniaturised products requires radical rethinking and restructuring of the underlying technologies, system engineering and product design approaches.

To address the above described trends and challenges the DFμA methodology is developed, serving the purpose of integrating product and microassembly process development. It aims in particular at increasing the efficiency of the product development process, decreasing the development time and the product and process cost, and enhancing the product quality.

1.2 Objectives

Microassembly technology has developed rapidly over the last few years and it is predicted that it will remain a critical technology. Microassembly positioned itself as a central process in manufacturing.

> *"The key challenge is to match the significant technological developments with a new generation of microproducts"* (Ratchev, 2007).

Fully in line with this challenge, it is the overall intention of this thesis to help overcome the barriers between single research products and production on an industrial level by developing a universal body of knowledge of DFA for the microdomain (see Figure 1).

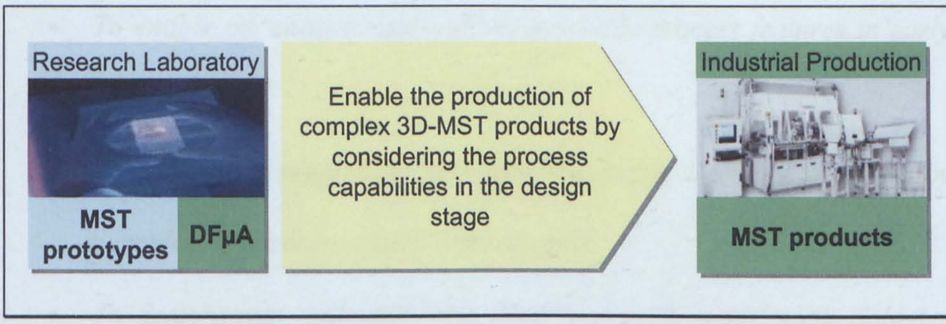

Figure 1: DFµA enabled transfer to market

Although the DFA is a widespread and important tool for the manufacturing industry, as well as for research and development at the macroscale, a common approach with similar tools for the microdomain is not available at present. This knowledge gap is addressed by the thesis and hence the main objective is formulated as follows:

To lay the foundations for a design for microassembly methodology (DFµA) that supports product design and process selection, hence facilitating the efficient assembly of complex three-dimensional miniaturised devices.

This primary research aim is supported by the following secondary targets which represent a number of key challenges. Addressing these targets contributes to the development of a new DFµA methodology:

- *To identify and develop robust models to support the DFµA methodology. Particular focus is laid on the formulation of a process capability model and a model of DFµA guidelines.*
- *To identify and formulate key constraints which are unique to the microassembly and need to be addressed when designing new micro-products*
- *To derive and develop design rules and guidelines that are focused on*

the microworld and its specific challenges.

- *To enable the consideration of key assembly process features in early design stages.*
- *To enable and support the selection of suitable assembly processes by considering process-related requirements.*
- *To demonstrate and verify the developed models and methodologies using pilot-applications and test cases.*

Achieving these goals provides a range of novel inputs to the research fields of DFM and DFA. In terms of making an industrial impact it is not only aimed at an increasing transfer of microproduct prototypes from the research laboratory to the market and decreasing time to market but is also intended to provide a means of evaluating the envisioned assembly processes early in the design stage. The following section describes the structure of this thesis and how it sets out to achieve the above described objectives.

1.3 Structure of the thesis

To achieve the described objectives a systematic approach has been adopted. This is reflected in the structure of this thesis, giving evidence of the research carried out (see Figure 2).

Essential for the identification of the knowledge gaps to be addressed is a comprehensive literature survey. That survey provides results of studies closely related to the work reported in this thesis and relates it to a larger ongoing dialogue in the literature about the topic of assembly and design in the micro-, and nanoworlds. In addition, it is the aim of the literature review to provide a topical framework, establishing both the importance of the work presented and a benchmark for comparing against other studies (Miller, 1991). The summary of the literature review is presented in Chapter 2 and contains the most important results, those used to define knowledge gaps.

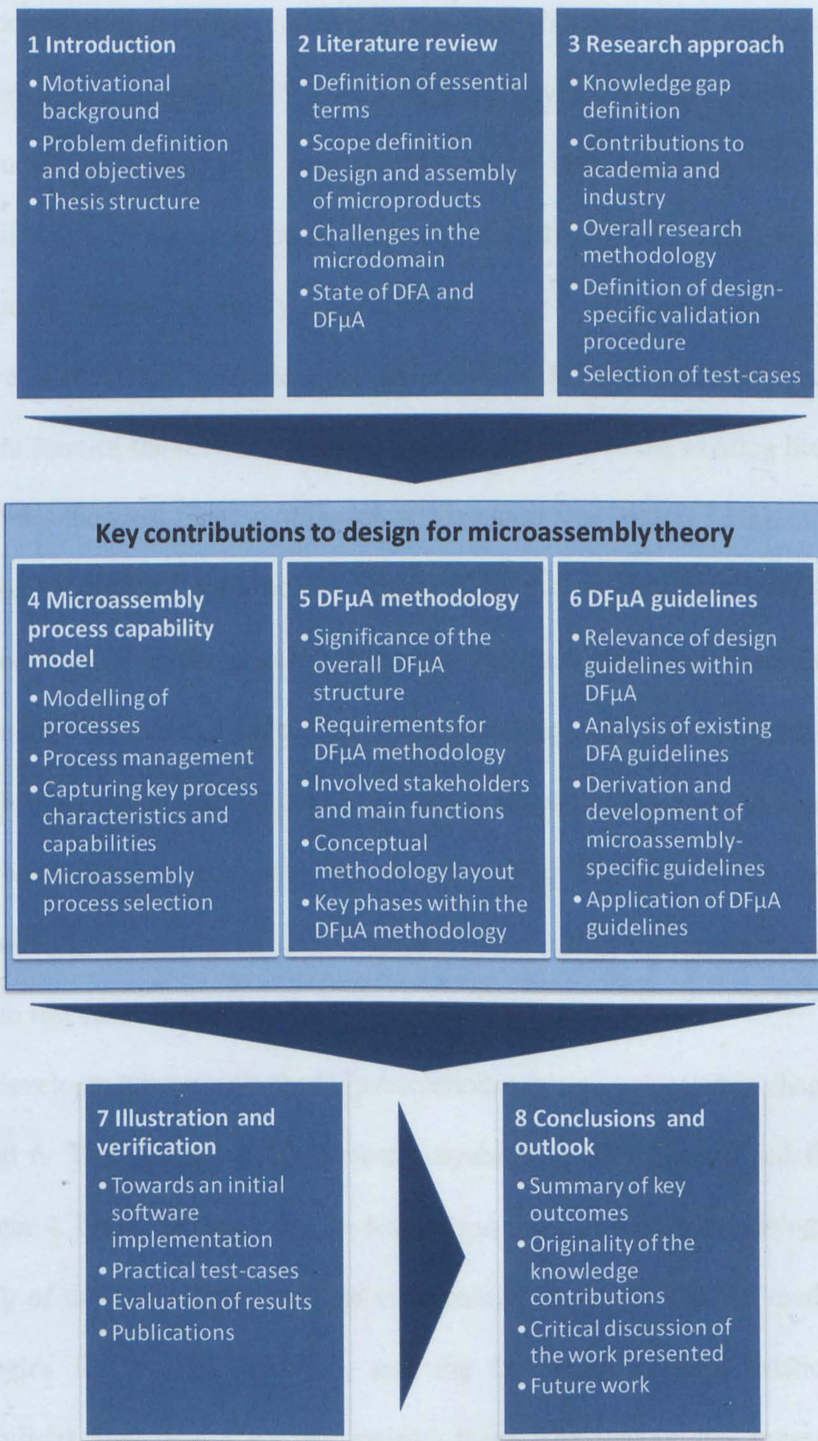

Figure 2: Thesis structure

The scope of this thesis is defined by identifying the boundaries between the nano-, micro-, and macrodomains. In the literature review, essential terms such as MST and *microelectro mechanical systems* (MEMS) are characterised and the meanings of assembly and design and their critical features are discussed. The environment in which the DFμA methodology is intended to be employed is elucidated, along with microworld-specific challenges, leading to the identification of the need for development and advancement of knowledge in product design and assembly process selection for microproduct development. Conventional DFA methodologies are analysed for their suitability and the current state-of-the-art in DFμA is evaluated. Analysis of the existing literature facilitates the identification of the knowledge gaps (see section 3.1.2).

Chapter 3 outlines the research approach to the development of a DFμA methodology. It carefully analyses the way the knowledge gaps identified can be addressed and the objectives achieved. The academic contribution to research is defined and the desired industrial impact of the work outlined. On that basis the research activities are described and the overall research methodology is discussed and explained. The validation approach and the chosen test cases are defined.

The developments towards the DFμA methodology are presented in chapters 4, 5, and 6. The microassembly process capability model is described first, in Chapter 4, because it provides the foundation for the entire methodology. The giving of that description consists in discussing basics in process modelling, strategies for process selection, and the key process characteristics and capabilities, including ways of capturing them. The chapter also presents the developed model for enabling selection and characterisation of microassembly processes. A framework to characterise the model's application to microjoining, -feeding, and handling is as well suggested.

Chapter 5 concerns the actual DFμA methodology. The conditions for a good DFμA methodology are described, and the methodology's layout and structure introduced in detail. Furthermore, the main functions and key phases of the methodology are explained. Special attention is paid to the integration of the microassembly process capability model and the development of further elements that are used within the methodology, such as support in product design. To enable such assistance in the design of microproducts it is important to include specific guidelines in the methodology.

Provided in Chapter 6 is a comprehensive analysis of conventional DFA guidelines, intended to explain how the microspecific guidelines have been formulated. The chapter also describes how these are implemented within the overall DFμA methodology.

The procedure of validating and illustrating the methodology, which includes applying it to practical test cases, takes place in Chapter 7. The thesis is concluded in Chapter 8, wherein evidence of the originality of the knowledge contribution achieved through the work presented is highlighted. Furthermore, the limitations of the findings are discussed, and possible future research work is outlined in giving an overview of upcoming trends and challenges with respect to the introduced DFμA methodology.

2 Literature review

This chapter gives an account of the literature review which was conducted to summarise relevant research and to collate and discuss key concepts related to DFμA. What is particularly important is to identify and examine the shortcomings of those concepts, so as to be able to clearly state the knowledge gaps now existing. It is the addressing of those knowledge gaps (see section 3.1.2) that constitutes the substantial research contribution made by this work. Of course, the literature review will as well discuss essential terms and define the way they are used here, so that their precise meaning is understood and the research findings can be communicated accurately.

The scope of the work is defined in section 2.1. The boundaries between the nano-, micro-, and macrodomains are discussed and identified here. In addition, the term microengineering is introduced and microproducts are characterised accordingly. In sections 2.2 and 2.3 the meaning and critical features of both *design* and *assembly*, fundamental areas for this thesis, are discussed and reviewed.

Section 2.4 gives an overview of the specific challenges appearing when assembling in the microdomain. Discussed here are the physical challenges resulting from object interaction, challenges resulting from the manufacturing environment, and demands resulting from automatic microassembly.

An analysis of the existing state of DFA with regard to the microdomain is carried out in Section 2.5 presenting the current state of DFμA. Conventional DFA methods and their applicability are reviewed and the limitations of these methodologies are analysed.

2.1 Scope definition

The *strategic research agenda* (SRA) of the *European Micro- and Nanomanufacturing platform MINAM* emphasises the research field's importance by stating that *"Micro- and nanomanufacturing technologies might well be the next industrial revolution"(Ratchev and Turitto, 2008)*. The focus of this thesis is the microdomain and it considers the nanomanufacturing technologies only peripherally. The justifying argument for setting these boundaries between the nano-, micro-, and macrodomains follows in section 2.1.2.

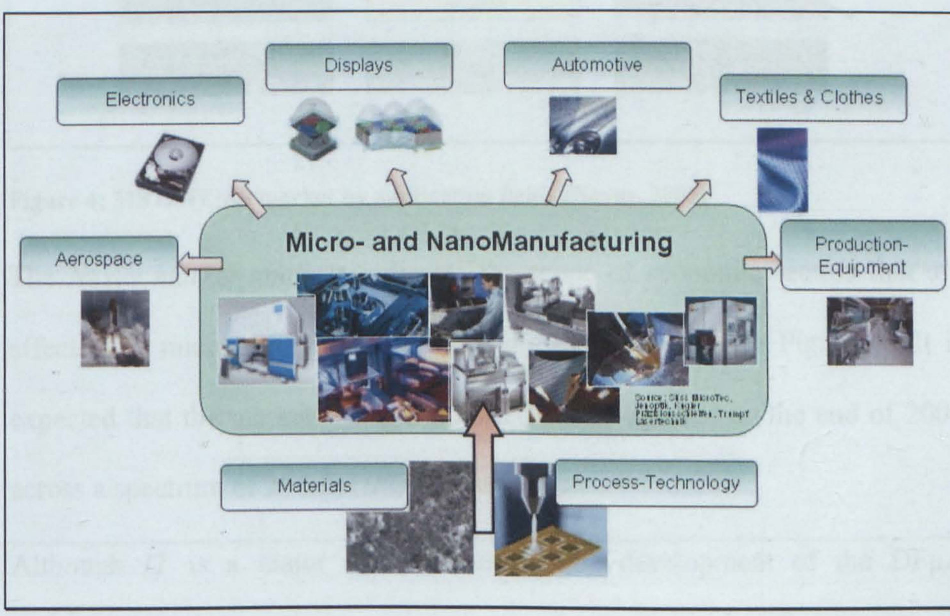

Figure 3: Different market sectors of nano- and micromanufacturing (Ratchev and Turitto, 2008)

Figure 3 illustrates the significance of the topic by providing an overview of the key micro- and nanomanufacturing applications in a range of market sectors such as aerospace, electronics, automotive, and production. The figure indicates that materials and process technologies form the basis of micro- and nanomanufacturing.

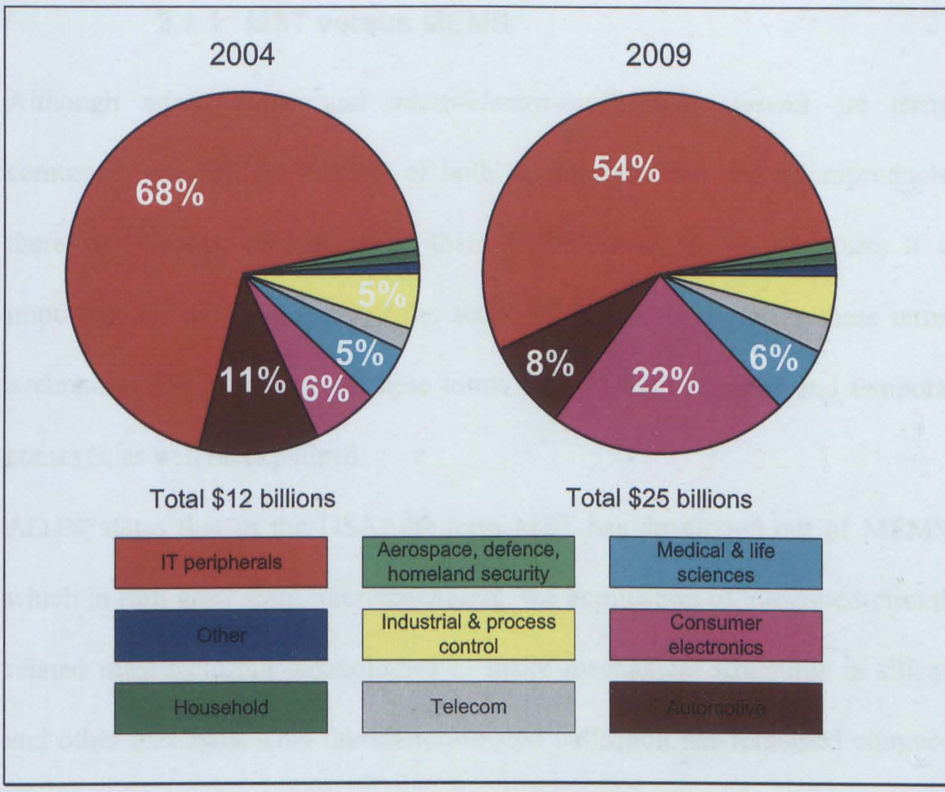

Figure 4: MST/MEMS market by application fields (Nexus, 2005)

The *Nexus market analysis* indicates the scope of economic sectors that are affected by micro- and nanomanufacturing technologies (see Figure 4). It is expected that the market will grow to $26 billion in total by the end of 2009 across a spectrum of 26 MST/MEMS products.

Although *IT* is a major market segment the development of the DFμA methodology is not aimed at silicon-based products. It is for this reason that areas of the methodology's application are more likely to be in the growing sectors of biomedical products or industrial & process control. This is also reflected by the choice of demonstrational products targeting key sectors of UK and European industry (see section 3.3.2).

In the course of defining the scope and focus of this thesis it becomes clear that the terms MST and MEMS have to be distinctively examined and defined.

2.1.1 MST versus MEMS

Although *microsystems* and *micro-electro-mechanical systems* are terms commonly used in the context of both microproduction and microproducts, there are varying definitions of them to be found in the literature. It is important for the discussion of the scope of the thesis to define these terms accurately. The meanings of these terms vary in both regional and temporal contexts, as will be explained.

ALLEN states that in the USA, the term MST has developed out of MEMS, which in turn grew from micromachining, the application of integrated-circuit-related manufacturing technologies to make mechanical structures in silicon and other materials. This fabrication-related definition has remained common all over the USA, and MEMS has been defined as a means of production rather than as describing components of a specific geometry or range of size. In Japan, a different conception of MEMS has evolved. Japanese efforts in MEMS are focussed on the device itself, rather than the manufacturing technologies (Allen, 2003).

SENTURIA points out that the term *microsystems* is predominantly used within Europe whereas MEMS is more common in the USA and increasingly in other places (Senturia, 2000). CECIL *ET AL.* point out that MEMS mechanisms normally contain silicon-based mechanical and electrical parts (Cecil *et al.*, 2007). Another, more detailed definition states that *"MEMS is the integration of mechanical elements, sensors, actuators, and electronics on a common silicon substrate through the utilisation of microfabrication technology"* (Joshi, 2000).

MEMS technology builds upon the existing microelectronics infrastructure to create components with micrometre-sized features (Cecil *et al.*, 2007, Joshi, 2000). Accordingly, manufacturing of MEMS originates in integrated circuit processing involving monolithic processes that require no assembly. Typical products manufactured through silicon-based techniques are, for example, accelerometers and inkjet printer heads (Krause *et al.*, 1996).

In that context, ANANTHASURESH calls silicon *"the old material"*, referring to the material being employed in microelectronics and integrated chip processing. He describes recent trends that suggest a rising interest in novel materials including ceramics, polymers, active materials, bio-materials, and metal-based alloys. Silicon on the one hand has advantages such as semiconductivity and good mechanical properties, on the other hand it is characterised by expensive production equipment, a lack of three-dimensional and freeform geometries, and difficulties in establishing the connection between microsystems and a macroenvironment (Malek and Saile, 2004, Ananthasuresh, 2000). Despite recent technological advances for integrated planar devices, many future products will require assembly from separate parts, due to required properties of different materials, the necessity for three-dimensional degree, or because of the kind of functional needs (Cecil, 2004, Hollis and Gowdy, 1998). Microassembly allows moving beyond these confines of silicon micromachining (Cohn *et al.*, 1998).

Microdevices which are characterised by incompatible or multi materials and unsuited complex geometries rely on assembly.

SENTURIA suggests that the terms MST and MEMS are these days used synonymously. Microsystems are described as *"very small systems"* or *"systems made of very small parts"* that perform some useful function, regardless of the way they are fabricated or of types of functionality. The term MEMS, in contrast, suggests that moving parts (mechanical) and either electricity or electronics must be included in the product (Senturia, 2000).

It can be concluded that the terms MEMS and microsystems are partly overlapping. However to avoid any kind of confusion it has to be stressed that the DFμA methodology presented in this thesis, is not concentrating on the well known *"old material"* silicon with its already highly developed mature manufacturing technologies, but rather supports the aim of moving away from silicon. The objectives of this thesis focus on three-dimensional multi-material microproducts (see section 1.2) that require assembly.

2.1.2 Boundaries between nano-, micro-, and macrodomains

This section establishes the basis for understanding the challenges arising in the microdomain, which are described in section 2.3. First, the scope of nanotechnology is delimited, in particular its borders and distinctions to the microdomain are defined. Second, the critical differences between the micro- and macrodomains are described. Defining the scope of the microworld sets a boundary to the conventional macroworld.

Nanotechnology

In nanotechnology classical physical principles are less relevant as molecular and atomic sizes are approached. Chemical aspects affect the production and the utilisation of nanotechnical structures. Contrary to classical chemistry, small quantities of, or single particles are crucial (Köhler and Fritsche, 2004).

KÖEHLER AND FRITZSCHE distinguish between nanostructures and microstructures by measurements of length. A narrow definition of nanostructures is their "*inclusion of structures of at least two dimensions below 100 nanometres*" (ibid.) A wider definition includes "*structures with one dimension below 100 nanometres and a second dimension below one micrometre*" (ibid.). Nanodevices are characterised by at least one functional component's being a nanostructure.

WILSON *ET AL.* answer the question of what nanotechnology is as follows: *"Nanotechnology is an anticipated manufacturing technology that allows [...] working with atoms. It will allow many things to be manufactured at low cost and with no pollution. It will lead to the production of nanomachines, that are sometimes also called nanodevices"* (Wilson *et al.*, 2002).

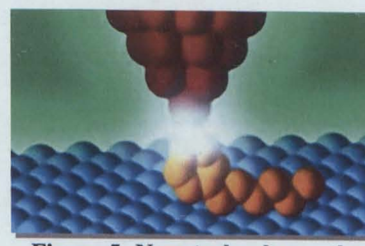

Figure 5: Nanotechnology - the principle of atom manipulation (NIST, 2006)

DREXLER defines nanotechnology as *"the principle of atom manipulation, atom by atom, through control of the structure of matter at the molecular level"* (Drexler, 1990). Figure 5 illustrates this ability of creating molecular systems with atom-by-atom accuracy.

The *nanotechnologies* definition most frequently used in the US by both government and -industry "*involves structures, devices and systems having novel properties and functions due to the arrangement of their atoms on the 1 to 100 nanometre scale*" (Foresight-Nanotech-Institute, 2006). Various disciplines contribute to nanotechnology, including molecular physics, materials science, chemistry, biology, computer science, electrical engineering, and mechanical engineering (ibid.).

CORBETT *ET AL.* describe nanotechnology to be the *"study, development and processing of materials, devices and systems in which structures in a dimension of less than 100 nanometres are essential to obtain the required functional performance"* (Corbett *et al.*, 2000).

Common to most definitions is the stressing of the idea of the manipulation of atoms, this suggesting nanotechnology as closely related to chemistry. To accentuate the difference between nanotechnology and microtechnology it is necessary to define microtechnology.

Microtechnology

Microtechnology, unlike nanotechnology, still follows physical principles. FERRARIS *ET AL.* define products in the field of MST by their having overall dimensions up to a few millimetres and components in the range of micrometres (Ferraris *et al.*, 2003). They do not refer to nanotechnology specifically. MASUZAWA *ET AL.* define the scope of microtechnology by claiming the term as applicable only to structures less than 500 micrometres in dimension (Mazuzawa *et al.*, 2002). However, the problem with defining microtechnology only by reference to size is pinpointed by ALTING *ET AL.*, who rightly observe that manufacturing capabilities change so rapidly as to be constantly overtaking the lower boundaries of range (Alting *et al.*, 2003). For that reason, they introduce the term *microengineering* which should contain *"the philosophy and the characteristics of a microproduct"* (ibid.). Accordingly microengineering is defined as "[dealing] *with development and manufacture of products, whose functional features or at least one dimension are in the order of micrometers. The products are usually characterised by a high degree of integration of functionalities and components"* (Alting *et al.*, 2003). This definition fits very well into this thesis, because it defines the range of products that will be dealt with and characterises DFμA as a part of the product development process in microengineering (see Figure 6).

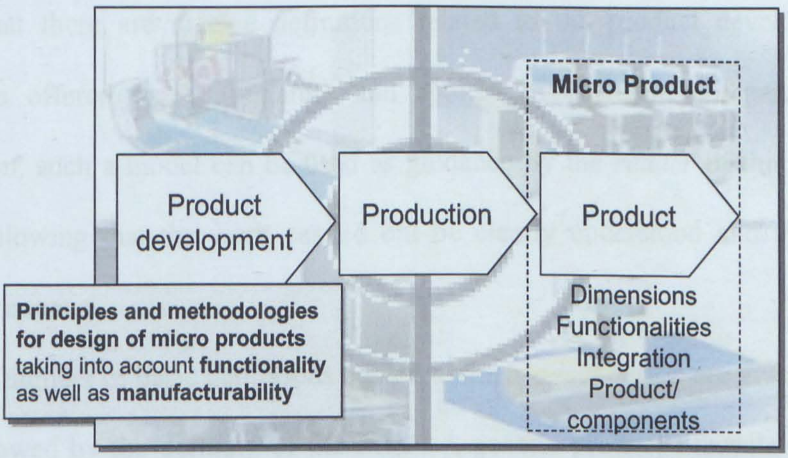

Figure 6: Allocation of DFμA within microengineering (adapted from Alting *et al.*, 2003)

It is generally acknowledged that the transfer of developed prototypes from a research laboratory to industrial production is delayed because of difficulties in developing cost-effective manufacturing processes (Popovic, 2004, Alting *et al.*, 2003, Hesselbach and Raatz, 2002).

Hence, it can be concluded that the relation between product design and production system design is not properly considered in the microdomain. Considering the critical importance of microassembly within the manufacturing process (see section 2.3) it becomes clear that a DFμA methodology which supports assembly process selection is needed.

2.2 Product design and development

In section 2.1 the thesis' scope has been defined in terms of product applications and dimensions. However, to understand the DFμA methodology's relevance, it is necessary to have a clear picture of where it is used within the *product development process*. Therefore, this section defines a *process development model* (PDM), to be used as a reference point for the methodological developments. The need for a reference model results from the fact that there are diverse definitions related to the product development process offered in the literature and applied by different companies. In addition, such a model can be used as guidance by the *reader* of this thesis, thus allowing that the work carried out be clearly understood and put into proper context.

First a number of basic definitions related to the *product design* are given. This is followed by the defining of the PDM. A generic product lifecycle and its implications for product design are then described (section 2.2.1). That having been done, the *product development process* is discussed and displayed (section 2.2.2). Recent problematic trends within the product development process are highlighted, and finally the implications for product design in the microdomain are summarised (section 2.2.3).

2.2.1 Product design

> *"Product design is a generic term for the creation of an object that originates from design ideas – in the form of drawings, sketches, prototypes, or models – through a process of design that can extend into the object's production, logistics and marketing"* (Slack, 2006).

This is a very broad definition. PAHL *ET AL.* identify *psychological*, *systematic*, and *organisational* aspects of design (Pahl *et al.*, 2007). From the *psychological* side, design focuses on creativity, while still considering knowledge and experience of the domain of interest as well as mathematics, physics, chemistry, mechanics, thermodynamics, electrical engineering, production engineering, materials technology, machine elements etc. In *systematic* respects, design aims at optimising a set of given requirements within constraints that are to a certain extent contradictory. Because objectives might vary over time specific solutions can only be improved for particular situations. From the *organisational* point of view, designing is a significant element of the product lifecycle (see Figure 7). This cycle is initiated by market demand (market pull) or a novel idea (technology push) (see Pannenborg, 1986, for an analysis of market pull versus technology push from the designer's perspective).

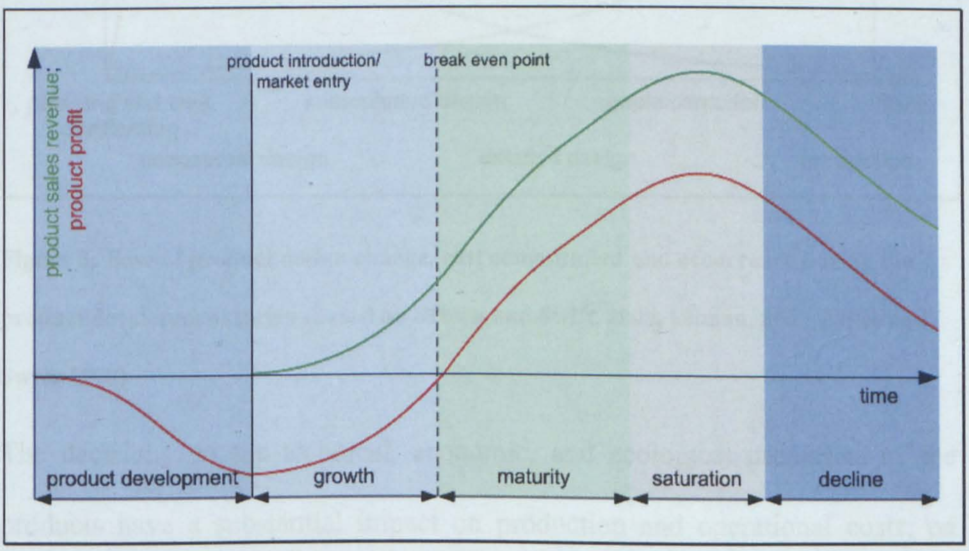

Figure 7: Classical product lifecycle

Figure 7 shows that the product development phase is an important part of the product lifecycle and that investment in this phase precedes potential success in the market. Accordingly, product development is of critical importance in any company. Production and assembly depend heavily on information from product planning, design and development. And, production and assembly knowledge and experience can influence product design and development. It is widely recognised that the product design stages have a significant influence on the production cost (e.g. Jared *et al.*, 2008, Eversheim and Schuh, 2005, Boothroyd *et al.*, 2002, Miles and Swift, 1998, Reichenwald and Conrat, 1993).

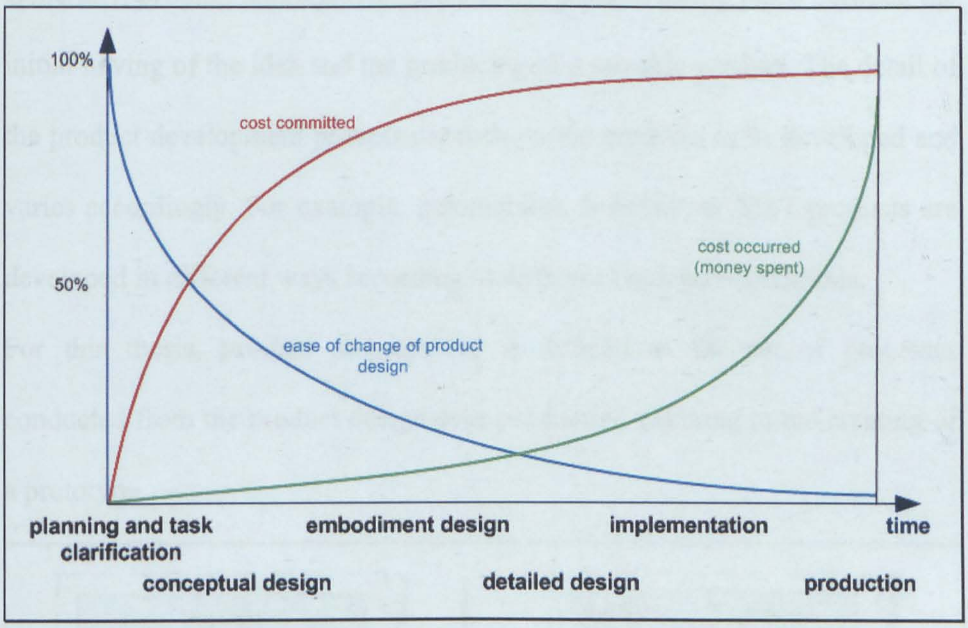

Figure 8: Ease of product design change, cost commitment and occurrence during the product development stages (based on Brown and Swift, 2008, Ullman, 2003, Miles and Swift, 1998)

The decisions on the technical, economic, and ecological properties of the products have a substantial impact on production and operational costs, on quality, and on production lead times (Pahl *et al.*, 2007). Up to 80% of the product costs are committed by the end of the concept design phase, see Figure 8 (Miles and Swift, 1998, Brown and Swift, 2008).

The early stages in the product design allow the easiest changes, therefore "[they are] *the ideal and only time to get manufacturing cost right*" (Miles and Swift, 1998).

After discussing the importance of product design, the next section situates product design within the whole product development process before describing the different product design phases in more detail.

2.2.2 Product development process

Generally, *product development* refers to the process taking place between the initial having of the idea and the producing of a saleable product. The detail of the product development process depends on the products to be developed and varies accordingly. For example, automobiles, software, or MST products are developed in different ways according to different boundary conditions.

For this thesis, *product development* is defined as the set of processes conducted from the product design over production planning to the creating of a prototype.

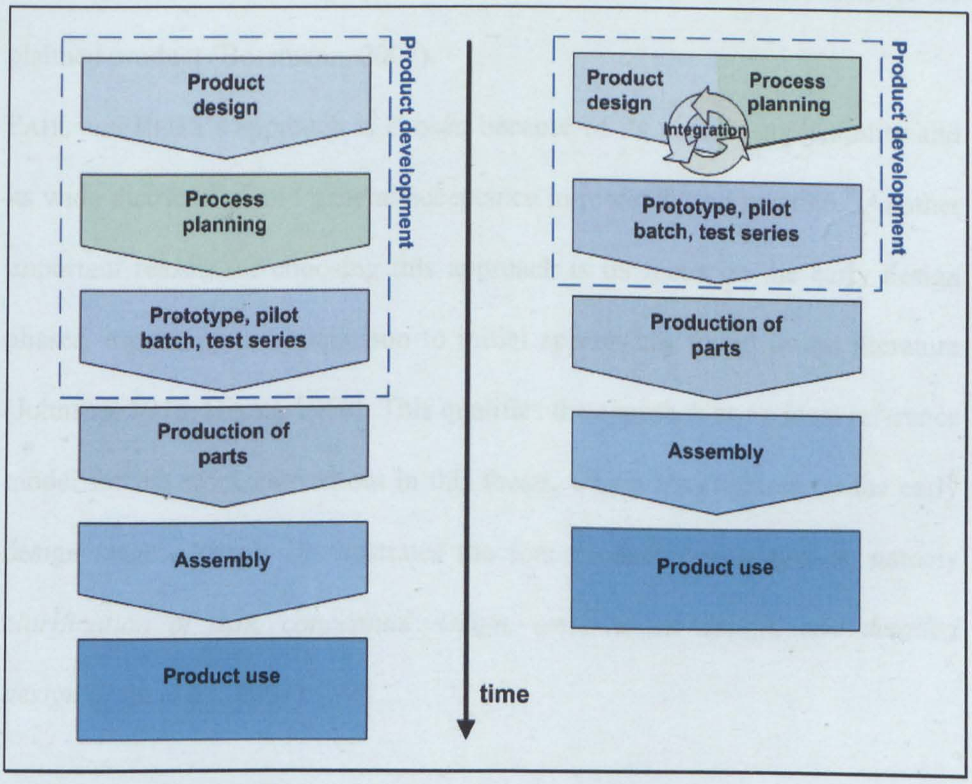

Figure 9: Sequential versus integrated product development in the product lifecycle (based on Pahl et al., 2007, Ullman, 2003, Reinhart et al., 1994)

Figure 9 illustrates the potential for the product development process to decrease time-to-market by integrating product design and production planning. The thesis pays particular attention to the product design phase, supporting the production planning of microsystems.

The actual *product design process*, being a major part of the product development process and the focus of the thesis, is defined according to PAHL ET AL. (see Figure 10). The *design process* represents all activities used to obtain the information necessary to fabricate a product. These activities include the research conducted into the composition of functions and parts of a product and into the way of integrating them, and the deciding of the detailed specification (VDI, 1993). The design process determines the exact product properties and results in the producing of a comprehensive documentation (drawings, bills of materials, part lists etc.) that allows for the realisation of the planned product (Bossmann, 2007).

PAHL and BEITZ's approach is chosen because of its generic applicability and its wide distribution and general acceptance in research and practice.[1] Another important reason for choosing this approach is its focus on the early design phases, especially in comparison to initial approaches found in the literature (Johnson, 1978, Dixon, 1966). This qualifies the approach as an ideal reference model for the work carried out in this thesis, which also focuses on the early design stages. Figure 10 illustrates the four product design phases, namely *clarification of task, conceptual design, embodiment design, and detailed design* (Pahl *et al.*, 2007).

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[1] Particularly in Germany this approach is seen as standard, in fact PAHL AND BEITZ were actively involved in formulating the *VDI-guideline 2221*, defining a *methodology for development of technical systems and products*.

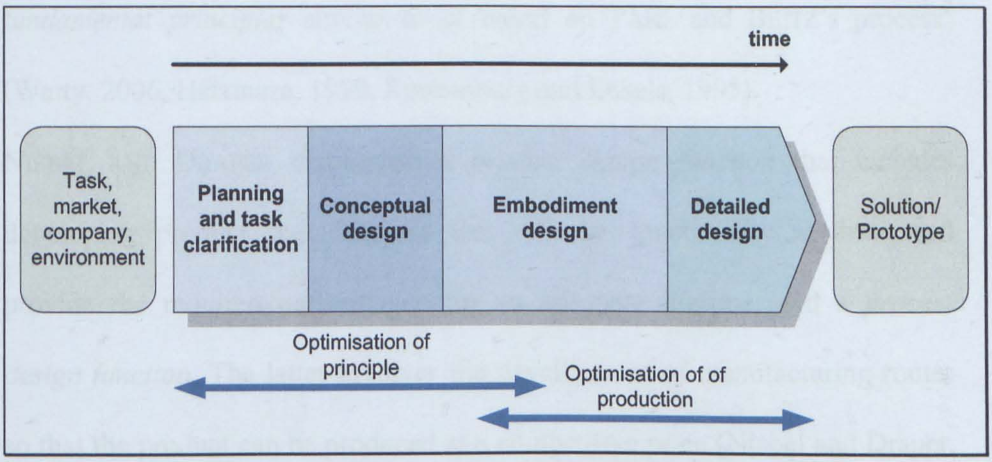

Figure 10: Steps in the product design process (according to Pahl et al., 2007)

Planning and clarification of the task starts by analysing the market and the environment within the company. It is followed by finding and selecting product ideas and formulating a product proposal, resulting in an elaborated requirements-list (design specification). *Conceptual design,* developing the principle solution, is a central stage in product design. (Shai *et al*., 2007). Significant problems and functional structures are identified, and working principles established. These processes result in conceptual variants which have to be evaluated against technical and economic criteria. The *embodiment design* aims at developing a product's preliminary form and selecting materials. Appropriate layouts are chosen, refined, and improved, and these as well are measured according to economic and technical criteria. Weaknesses of this initial layout are then eliminated and a preliminary parts list is created, resulting in the definitive layout. In the *detailed design* phase drawings and part-lists are created (Ulrich and Eppinger, 1995). On this basis the production and operating documents are defined. WATTY analyses a number of other product design models found in the literature and states that they are in their *fundamental principles* similar to or based on PAHL and BEITZ's process[2] (Watty, 2006, Hatamura, 1999, Roozenburg and Eekels, 1995).

NIEBEL AND DRAPER distinguish a *product design function* that includes developing product specifications that will be functionally accurate and provide the required performance for an adequate lifetime, and a *process design function.* The latter involves the development of manufacturing routes so that the product can be produced at a competitive price (Niebel and Draper, 1974). The positive effects that concurrent product and process planning can have on industrial competitiveness have been analysed by a range of investigators and the integration of product design and assembly planning is seen as crucial (Nevins and Whitney, 1989). Nevertheless, ZHA and LIM *ET AL.* argue in their literature reviews on the topic that due to the complexity of the technical and economic interactions between product design and process planning, *there is no mature integrated environment available* (Zha, 1999, Lim *et al.*, 1995).

2.2.3 Product design in the microdomain

As described in the previous section, once the product is designed it is very difficult or costly to go back and make alterations. This means that the product is for the most part irreversibly defined (Schuhmann, 1988, Radtke, 1995). Therefore, the product design decides the success of a product throughout the whole product lifecycle. Even small financial input in the design phase can open up enormous potential for the whole lifecycle (Düchting, 2005). Design

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[2] WATTY compares the models of PAHL/BEITZ, ROTH, KOLLER, RODENACKER, VDI 2221, HATAMATURA, AND ROOZENBURG

of MST products is characterised by a high degree of integration of both functions and components making it a very knowledge-intensive area.

In addition, there is a lack of *standard* parts and assembly technologies available for use by MST product design teams due to (Watty, 2006):

- The complexity of microsystems
- The continuous advancement of technology in MST (as described in section 2.1.2)
- The need for application-specific solutions

The lack of standard processes and parts leads to increased cost and risk of failure, particularly within the product development process but also in the production stage. This in turn leads to a reduced take-up for MST products. It is a commonly made argument that the introduction of standards could increase market growth (Leach *et al.*, 2003). However, enterprises which develop and produce microsystems need to get a monetary return for their investment. An early introduction of standards in an emergent industry *"does not allow pioneers to recoup their R&D investment and garner profit, unless they are provided with a royalty for their hard-won intellectual property"* (Leach *et al.*, 2003).

Small- and medium-sized enterprises (SME) in particular, although being the backbone of European industry, have limited resources available for product development. Because of this, GENTNER stresses the need for more efficient use of existing research and development resources (Gentner, 1994). Figure 11 illustrates this need by breaking down the engineers' activities within the product development process. The fact that engineers presently spend only 11% of their time engaged in what are properly *engineering* activities amply demonstrates the potential for making savings through the introduction of more efficient organisational processes.

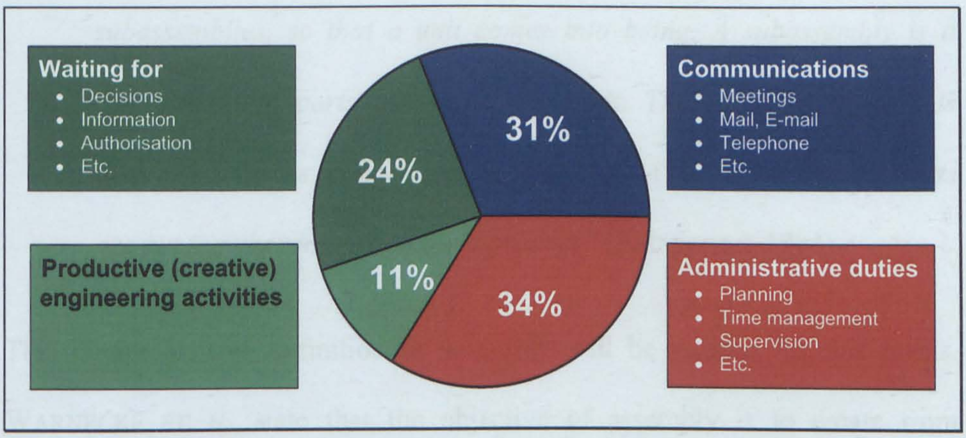

Figure 11: Engineering activities in the product development process (Harmon, 1992)

Especially in the microdomain, the need to spend time on communications and waiting for decisions arises out of the requirement for cross-disciplinary knowledge transfer and sharing, and thus the involvement of different parties. This thesis seeks to identify how best to address these issues in the field of microassembly.

2.3 Assembly in the microdomain

To enable the development of microassembly focussed design approaches it is important to understand the meaning of assembly and its role within manufacturing science. WHITNEY points out that assembly is much less studied than the manufacturing processes employed in making individual parts (e.g. turning or moulding). Moreover, assembly is "[the] *least understood process in manufacturing*" (Whitney, 2004).

Challenges in microassembly are often distinct from those attending macroassembly because of differently occurring physical behaviour, different levels of maturity in the technology, and microspecific processes.

2.3.1 Fundamentals in microassembly

"Assembly is defined here as bringing together parts and/or subassemblies, so that a unit comes into being. A subassembly is a composition of parts into a product unit. The assembly process is determined by the manner and the sequence in which the product parts are put together into a complete product" (Rampersad, 1994).

This comprehensive definition of assembly will be utilised for this thesis. WARNECKE *ET AL.* state that the objective of assembly is to create from individual parts a product of higher complexity and with specified functions, and to do so within a given period of time (Warnecke *et al.*, 1975). Each definition complements the other and comports well with the stated purpose of this thesis.

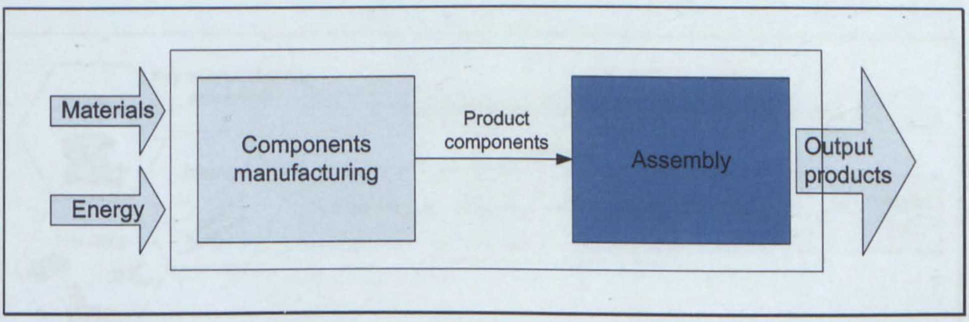

Figure 12: Assembly as part of the production process (adapted from Rampersad, 1994)

Figure 12 shows assembly as part of the production process, where the product parts are put together into subassemblies or into final products. It is often the *"weakest link"* (Rampersad, 1994) in the production process, although it constitutes a substantial portion of both the total production costs and throughput time. Assembly combines all upstream processes of design, engineering, manufacturing, and logistics to build an object that carries out a function, and therefore can be seen as *"the capstone process in* *manufacturing"* (Whitney, 2004).

The main difference between assembly in the macro- and in the microworld is the required positional precision. Microassembly deals with the assembly of small components into systems, with accuracies in the order of micrometres (Yang *et al.*, 2001, Scheller, 2001), typically 0.1-10 micrometres (Cecil *et al.*, 2007, Tichem *et al.*, 2004). Part dimensions span from sub-millimetres up to a few millimetres, part features can be in the micrometer range. Forces involved in microassembly can be significant down to a few nanonewtons (Lu *et al.*, 2006). Typically four to six degrees-of-freedom (DOF) are needed for three-dimensional microassembly tasks (Yang *et al.*, 2001). For the purpose of this thesis the microassembly processes considered are *feeding, handling,* and *joining*, these representing processes that are critical in microassembly (see Figure 13).

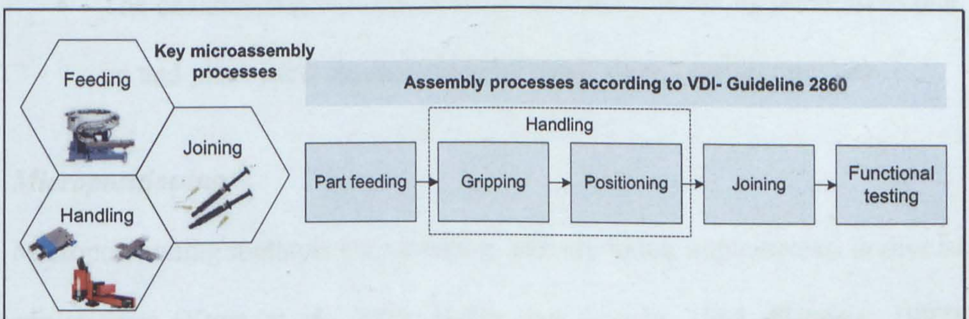

Figure 13: VDI 2860 (VDI, 1990) vs. key microassembly processes

Microassembly in industry is increasingly often done using robots and assembly systems based on Cartesian axes (Hesselbach *et al.*, 2003). Such systems are often developed according to customer-specific requirements for a single product and thus have very low levels of flexibility whereas high flexibility is considered to be essential for MST products because a wide range of products, with very different functions, are to be produced in relatively small numbers.

2.3.2 Microhandling

In general terms, handling can be described as the positioning, and the temporary holding of geometric objects within a coordinate system (VDI, 1990). According to LU ET AL. handling an object requires the ability to observe, position, and transfer the object (Lu *et al.*, 2006). This description of handling includes microgripping and -positioning. The former is used to pick up the object and place it in a different position, while the latter is used mainly for alignment but also for transport. HOLLIS AND GOWDY identify two critical problems to be addressed (Hollis and Gowdy, 1998):

- The difficulty of accurately aligning parts to be mated, regardless of their size
- The challenges presented to the production process by the need to pick up and place parts characterised by small sizes, (see section 2.4)

Micropositioning

Micropositioning methods are maturing, and are being implemented in diverse applications (Yang *et al.*, 2001, Hollis and Gowdy, 1998, Danuser, 1997). Good positioning systems "[should] *reduce the complexity and increase the speed and robustness of subsequent microassembly operations*" (Yang *et al.*, 2001). In addition, positioning systems have to provide accuracies from 0.1-10 micrometres (see section 2.3.1). The need to fulfil these requirements typically limits the commercially available positioning systems to linear and rotary axes (Scheller, 2001). The advantage conferred by this is the securing of high degrees of modularity, this due to the use of standard axes. Such positioning systems providing high accuracy are available on the market off-the-shelf, and are being continuously further developed, e.g. by Physik Instrumente (PI) GmbH & Co. KG, Newport, Klocke Nanotechnik, etc. (see Figure 14).

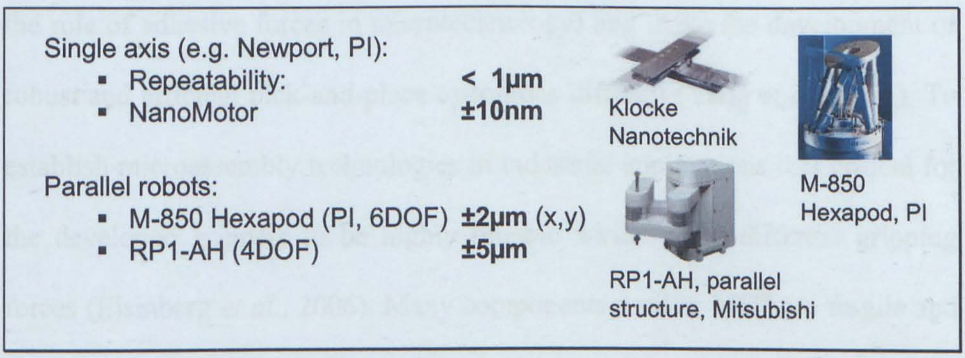

Figure 14: Positioning accuracies - state-of-the-art

While the employing of linear stages can be understood as one possible solution, combining several precise linear systems to achieve 6 DOF requires significant effort in integrating them. Another solution is to use robotics for part positioning. Using robots provides a relatively big and flexible workspace and up to 6 DOF. However, only a few original equipment manufacturer (OEM) of robotics offer equipment which provides the above mentioned absolute accuracies (Hesselbach and Raatz, 2002, Scheller, 2001). Both solutions are characterised by high cost, resulting from the use of precise axes. Hence, SCHELLER suggests a third approach, that of using cost-effective axes, the inaccuracies of which should be compensated for by additional fine adjustment units such as piezostacks (Scheller, 2001). A further option is equipping the systems with vision systems or force sensors to improve accuracies.

Microgripping

Microgripping is one of the most characteristic processes in microassembly. It is based on physical principles producing the forces needed to pick up and keep a part in a certain position with reference to the gripper (Tichem *et al.*, 2004). Forces other than gravity are operating on the part (see section 2.4.1 for the role of adhesive forces in microtechnology) and make the development of robust and efficient pick-and-place operations difficult (Yang *et al.*, 2001). To establish microassembly technologies in industrial applications it is critical for the developed grippers to be highly reliable whilst using different gripping forces (Eisinberg *et al.*, 2006). Many components used in MST are fragile and sensitive to mechanical forces, for example surface-structured components, meaning that the market availability of such grippers is quite limited (Scheller, 2001).

Figure 15 provides an overview of microgripping principles. These principles include some that are also used in the macrodomain, such as friction-based, form-closed, and magnetic gripping.

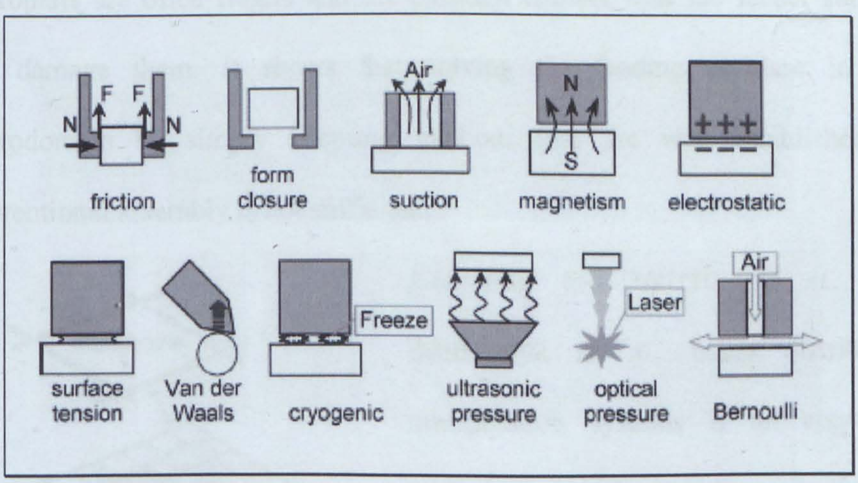

Figure 15: Principles for microgripping (Tichem *et al.*, 2004)

According to the findings of a range of investigations carried out by universities and other research institutions, four gripping methods seem suitable for microassembly (Scheller, 2001): vacuum and piezoelectric grippers, gripping structures made of shape memory alloys (SMA), and grippers that utilise surface tension forces. SMA grippers are problematic because of their long cycle time (due to their temperature behaviour). This limits their suitability for automatic assembly (of high volumes).

Various task-specific microgrippers based on the principles illustrated exist as prototypes in research environments. Microgrippers used in industry are the same as for bigger parts, they are only adapted in size (e.g. pneumatic or motor driven fingers).

2.3.3 Microfeeding

The most common feeder in macroassembly is the vibratory bowl feeder. Accordingly, some microfeeding solutions based on that working principle have been proposed (Biganzoli and Fantoni, 2005). Nevertheless, vibration is not considered to be an effective approach for microfeeding because microparts are often fragile and the constant contact with the feeder surface can damage them. It shows that solving the feeding problem in the microdomain by simply adopting methods that are well established in conventional assembly is not sufficient.

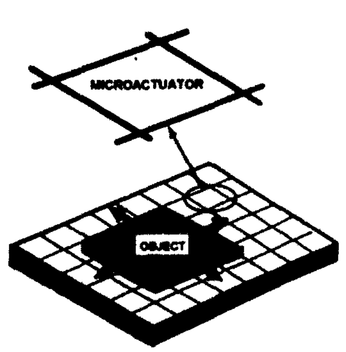

Figure 16: Distributed manipulation (Konishi and Fujita, 1994)

According to TURITTO *ET AL.* and BÖHRINGER *ET AL.* using distributed manipulation systems is an approach commonly used in the microworld (Turitto *et al.*, 2006, Böhringer *et al.*, 1994). Distributed systems induce motion on components by applying many external forces (Moon and Luntz, 2006). Through the cooperation of a microactuator array, objects can be transported in different directions and orientations (see Figure 16). Through the cooperation of the single motion pixels several functions such as transport, orientation, alignment, and even some elementary assembly operations can be realised (Konishi and Fujita, 1995). Distributed manipulation can be based on techniques such as actively controlled arrays of air jets (Turitto *et al.*, 2008, Konishi *et al.*, 2003, Yim *et al.*, 2000) and planar micromechanical actuator arrays (Suh et al., 2000, Tadokoro et al., 2000, Böhringer et al., 1994). Due to the reduced weight of the parts, contactless manipulation seems to be a possible approach for microassembly (Turitto *et al.*, 2006, Biganzoli and Fantoni, 2005, Zhou *et al.*, 2005).

Parts can also be provided in trays or magazines. In the macroworld, components, which are sensitive to contamination or mechanical damage, are often provided in such magazines (e.g. optical components), where the parts rest in cavities. However, for automatic microassembly this is very problematic due to the lack of definition of position and orientation. SCHELLER formulated requirements for magazines or trays that provide optical microcomponents (Scheller, 2001). These can be adapted and transferred to other MST components. Therefore magazines need to:

- Provide a precise pick up position of the component.
- Avoid damage or contamination of the sensitive part surfaces
- Enable easy loading of the magazine (manual)

A basic approach to feeding of microparts is focussed on trays with precise cavities matching the component form (see Figure 17). This kind of tray needs to be designed specifically for each different component. DIN 32561 (DIN, 2003b) provides a standardised framework for these trays, which take workpieces in an orderly manner and can be used for storage, transport, and handling. The pallet frame equals the dimensions of a silicon wafer, assuring transferability to microelectronic facilities, such as standardised handling systems and semiconductor production equipment.

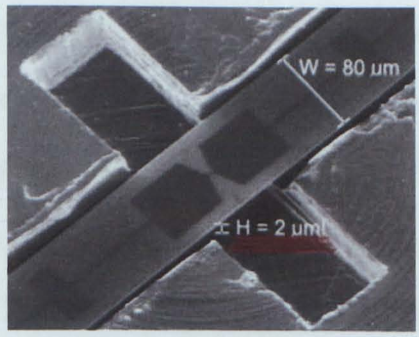

Figure 17: Trays – left, with form-fit cavities for optical components (Eberhardt *et al.*, 1999), right, with gripping slots (Klocke, 2008)

2.3.4 Joining of microparts

The term *joining* describes the process of durably connecting at least two previously separate workpieces, resulting in a newly formed part (DIN, 2003a). Because joints occupy space, require extra fabrication steps, and are hard to implement on small scales, the ideal solution would be to avoid assembly altogether (Van Brussel *et al.*, 2000). However, this is often unfeasible for technological and economic reasons and cannot be done in the microdomain when different materials are needed and complex three-dimensional structures are to be realised. In the microworld these joints have to fulfil functional roles, such as electrical conduction or sealing the component (ISF, 2008). Although simply downscaling existing joining mechanisms does not seem to be a promising approach, there are a few research groups working towards solutions of this type (e.g. Figure 18). GONZALES *ET AL.* have reported a range of microjoining concepts that use microfabricated dovetail joints (González *et al.*, 1998).

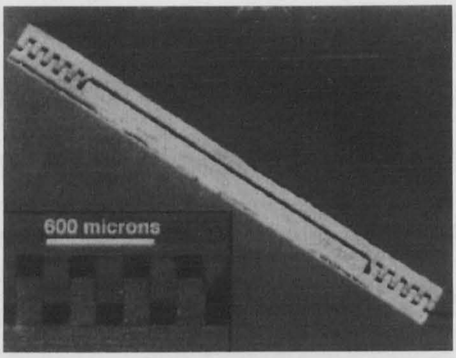

Figure 18: Finger joints (González et al., 1998)

It is generally acknowledged that adhesive bonding is the most appropriate process for the joining of microparts. In the bonding process an organic layer is used to join the parts, forming a solid compound. The properties of this bond depend on the characteristics of the adhesive used (ISF, 2008).

> *"In many instances, adhesive bonding is the only bonding technology feasible in the micro-world."* (Klocke and Gesang, 2002)

This is mainly due to the advantages of adhesive bonding in addressing the microdomain requirements described above, which can be summarised as follows (Klocke and Gesang, 2002):

- Joining of different materials
- Multi-functionality of the joint
- Low heat/cold joining
- Low mechanical stress and even stress distribution
- Insulation of parts, no corrosion

2.4 Challenges in the microdomain

After describing the state-of-the-art in microassembly and related requirements this section highlights additional difficulties and challenges associated with the microdomain. It is essential to consider these aspects in the development of a DFμA methodology.

2.4.1 Sticking effects

In addition to the distinctions already described, a very important difference between assembly in the macro- and the microdomains is related to the mechanics of object interactions due to scaling effects (Van Brussel *et al.*, 2000, Fearing, 1995, Sato *et al.*, 1995, Ando *et al.*, 1991). In the microworld, surface-related forces, such as *van der Waals forces*, *surface tension forces,* and *electrostatic forces* have a far greater effect than the gravitational forces that in this context are essentially negligible. The common microassembly literature refers to BOWLING and ISREALELACHVILI's explaining these forces (Bowling, 1988, Israelachvili, 1974). Because of this scaling behaviour, handling in the microworld distinguishes itself from that in the macrodomain, particularly when components to be manipulated are less than one millimetre in dimension. The surface forces could be used to pick up the component, however, they are very difficult to control and are likely to disturb the process. The part might jump to the gripper and lose orientation, or stick to the gripper such that releasing the parts becomes difficult (Tichem *et al.*, 2004, Van Brussel *et al.*, 2000). ARAI *ET AL.* report that the van der Waals, surface tension, and electrostatic forces depend on "*environmental conditions, such as humidity, temperature, surrounding medium, surface condition, material, and relative motion*" (Arai *et al.*, 1998).

Figure 19 shows the adhesive and gravitational forces as functions of the object radius. The object picked up by a gripper with flat jaw surfaces is a silicon sphere. It is clearly shown that forces resulting from surface tension such as capillary forces (De Lazzer *et al.*, 1999) are the most prominent. It is mainly these that are responsible for sticking effects between components.

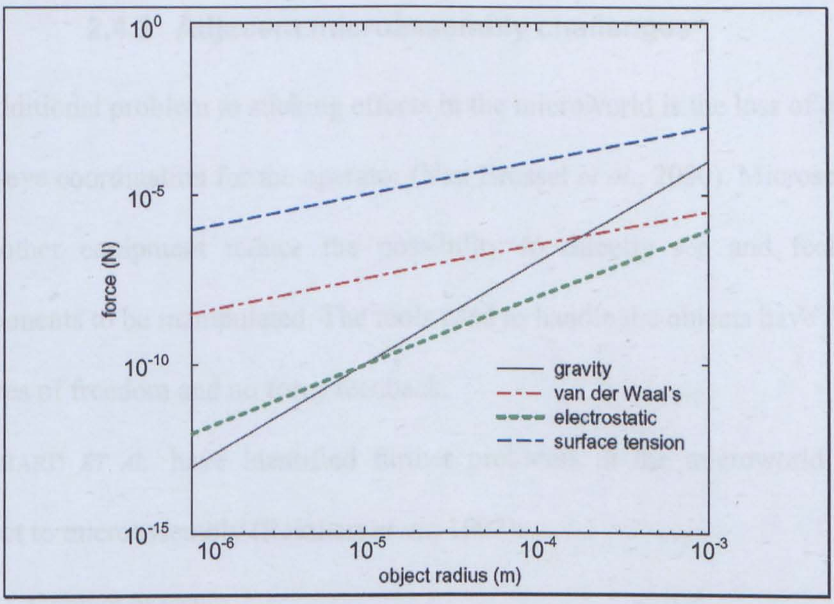

Figure 19: Forces acting on microstructures (Fearing, 1995)

To enable accurate placement, the adhesion forces should be significantly lower than the gravitational forces. Surface tension forces have to be avoided or minimised due to their overriding nature in this domain.

LAMBERT has analysed the importance of forces in microassembly with regard to the interaction distance covered by the respective forces, based on LEE'S classification of forces (Lee, 1991). LAMBERT concludes that capillary forces are of the *"utmost importance in microassembly"* (Lambert, 2007), as illustrated in Table 1.

Table 1: Forces according to their interaction distance (Lambert, 2007)

Interaction distance	Predominant force
Infinite range	Gravity
From a few nm up to 1 mm	Capillary forces
>0.3 nm	Electrostatic forces
0.3 nm < separation distance < 100 nm	Van der Waals
<0.3 nm	Molecular interactions

2.4.2 Adjacent microassembly challenges

An additional problem to sticking effects in the microworld is the loss of direct hand-eye coordination for the operator (Van Brussel *et al.*, 2000). Microscopes and other equipment reduce the possibility to directly see and feel the components to be manipulated. The tools used to handle the objects have fewer degrees of freedom and no force feedback.

REINHARD *ET AL.* have identified further problems in the microworld with respect to microassembly (Reinhart *et al.*, 1997):

- Contact pressure
- Tolerances
- Interference factors

Because of the very small surface areas for gripping and joining the surface pressure in the contact region can damage sensitive objects (even when applying low forces). Furthermore, assembly of microparts has to cope with possible low component tolerances. Interference factors such as contamination, vibration, or temperature changes can lead to positional errors. Besides external environmental sources (milieu-related), internal influences (caused by the equipment or factory) such as vibration and heat etc. have to be taken into account. In addition, electrostatic effects on the surface of an object could attract dust to the parts. This phenomenon not only interferes with the object's motion but can also contaminate its surface.

Finally, the cost of manipulation is an important issue in the microdomain, given that up to 70% of the production costs of miniaturised systems or hybrid systems occur in assembly (Hesselbach, 2000, Koelemeijer and Jacot, 1999).

2.4.3 Demands in automatic microassembly

In today's industries manual microassembly is still a relatively common feature, e.g. many factories contain microscope workplaces (Hesselbach *et al.*, 2003, Reinhart *et al.*, 1997). Chiefly because direct hand eye coordination is lost, but as well because of human factors such as fatigue, production in the microscope workplace is time consuming and costly and it is almost impossible to provide consistent high quality. Increasing complexity and miniaturisation of products themselves or sub-products to be incorporated in larger products, creates a need for the providing of technologies and systems for micromanipulation and automated microassembly (Hollis and Gowdy, 1998). Furthermore, to tackle any producing company's key challenges of providing products at a *competitive price,* with *competitive quality,* and in a *competitive delivery time*, it is necessary to aim for *high productivity*, *constant* and *high product quality,* and *short throughput times* (Rampersad, 1994). Because manual assembly cannot provide these production aims, it is important to put efforts into realising automatic microassembly facilities, enabling future developments within MST (Fatikow *et al.*, 2004). In addition, growing volumes and tighter tolerances render manual assembly increasingly unsuitable. SCHELLER describes this for the area of microoptics assembly, where manual workplaces can no longer provide sufficient quality (Scheller, 2001).

KOELEMEIJER CHOLLET *ET AL.* presented a study, modelling microassembly costs, which supports the argument above (Koelemeijer Chollet *et al.*, 2003). Figure 20 summarises the results, comparing the product assembly cost for manual assembly and for assembly on a flexible assembly system for different batch sizes.

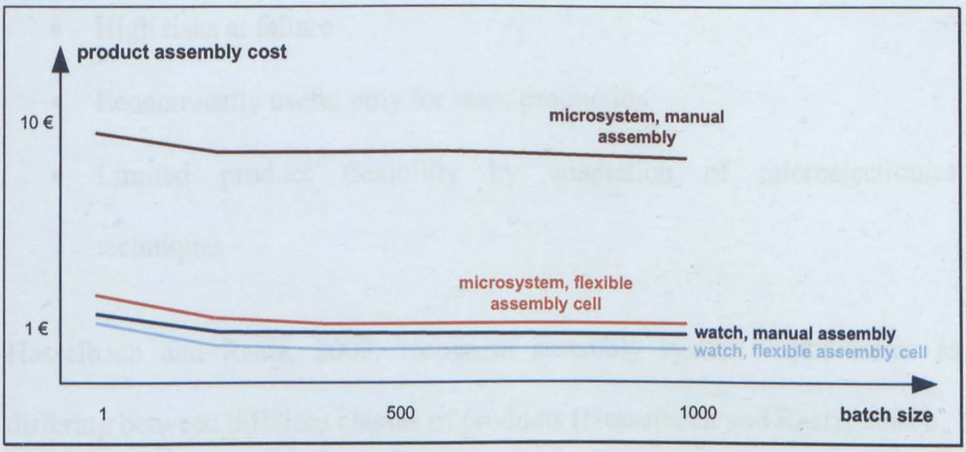

Figure 20: Flexible cell versus manual microassembly - cost and batch size (Koelemeijer Chollet *et al.*, 2003)

In fact, the *"mikroPRO"*[3] study, dealing with the international state-of-the-art of microproduction technology, points out that worldwide the *"development of economically efficient assembly processes"* is a major drive for automating microassembly processes (Hesselbach and Raatz, 2002). Other stated reasons for automatic microassembly are *"enabling new technologies"*, *"achieving higher accuracies"*, and *"reaching constant high quality"* (ibid.).

Although several demonstrator products showing the enormous potential of MST have been developed worldwide, it has so far not been possible to transfer that potential into industrial practice. The following key problems have been identified in the area of microfabrication (ibid.):

- High complexity of products and processes
- Extremely small sizes of devices
- Large range of knowledge in diverse technical fields

[3] A study about the international state-of-the-art of microproduction technology, carried out by Technical University Brunswick (IWF), University Karlsruhe (WBK) and Fraunhofer Insitute (IPT)

- Necessary high investments
- High risks at failure
- Economically useful only for mass production
- Limited product flexibility by adaptation of microelectronics techniques

Hesselbach and Raatz, 2002, recognise assembly system requirements as differing between different classes of products (Hesselbach and Raatz, 2002):
Products which cannot be produced manually: automatic microassembly needs to **enable technology,** i.e. there is a need for equipment characterised by

- High accuracies (better than 1 μm)
- More than 4 degrees of freedom (DOF) and
- The capability to assemble 3D

Products which are already established on the market: **cost effective manufacturing of higher quantities is necessary**. For cost effective manufacturing of minimised products, there is a need for equipment which improves cycle times. For that reason, equipment is needed which provides:

- Constant quality and accuracy respectively
- Either higher speed or
- Shorter distances to be covered

For production with a low diversity of product variants **cost effective mass production is needed**. Because there is demand for producing changing products the need arises for **high flexibility** of assembly systems. Industry demands solutions to compete with the wage difference between Europe and low wage countries with manual production. For that reason the whole manufacturing process chain should be linked and automated, i.e. a DFμA methodology needs to support linking the manufacturing process chain.

2.5 State of DFA in the microdomain

The previous sections have explained the need for a DFμA methodology that considers microassembly process characteristics and selection support, and for guidelines for assembly-oriented microproduct design in the early design stage. The object of this section is to analyse the current state of DFA in the microdomain, which is an important step toward defining the knowledge gaps to be addressed (see section 3.1.2).

In order to do this, the section follows a systematic approach: first, a general introduction to DFA is given, including general background, the history of DFA and its industrial significance (section 2.5.1). That having been done, the results of a review regarding DFμA approaches that are available or under development in other research groups are described (section 2.5.2). Because the current state-of-the-art in DFμA is not sufficient, commonly accepted and widespread DFA methods are introduced and analysed (section 2.5.3) with reference to their suitability to tackle microassembly-specific challenges (see section 2.4).

2.5.1 Background with regard to DFA methods

In general, DFA can be described as product design that aims at optimising the manual or automatic assembleability (assembly-oriented design). WHITNEY describes DFA as a representation of knowledge, procedures, analyses, metrics, and design recommendations, with the purpose of improving the product in the assembly domain (Whitney, 2004). By tradition it was thought that designers should have satisfactory knowledge of the manufacturing processes, in order to avoid unnecessary additional cost, (Mei, 2000) or even to make up for weaknesses in product and assembly design (Whitney, 2004). Moreover, the transition from the conceptual idea to the final manufactured product was sequential from the design to the manufacturing department, which organisational process necessitated time-consuming and costly design iterations (see section 2.2.1). The growing complexity brought by the use of automatic machinery, and especially assembly robots, as well as increasing market pressures (shorter time-to-market etc.) were reasons for focussing more on the assembly itself (Whitney, 2004, Mei, 2000).

The main goals of DFA can be summarised as: to make assembly *easier, less costly, simpler*, and *more reliable*. These objectives are supported by a range of DFA guidelines.[4] The most common and important guidelines can be summarised as follows:

- Decreasing the amount of components (resulting in fewer processes across the whole supply chain). REDFORD AND CHAL see the total number of parts in a product as a key indicator of product assembly quality (Redford and Chal, 1994).
- Fewer joining processes (e.g. use of snap fits)
- Avoidance of adjustment processes (e.g. use of chamfers)
- Standardisation of components and their interfaces
- Avoidance of flexible parts within automated assembly

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[4] In Appendix C an extensive amount of guidelines is presented and analysed for their suitability for microassembly.

- Avoidance of tight tolerances

An outline of the progress of DFA, giving both a history and a projection of future trends, is displayed in Figure 21. The forerunners of DFA include HENRY FORD, who 100 years ago was among the first manufacturers to intentionally focus on the assembly process. That attending to the way in which the assembly process could be changed in order to allow that cars be assembled both more easily and more reliably led to his early cars' having simpler designs and fewer parts than his competitors' (Herbertsson, 1999, Hounshell, 1984).

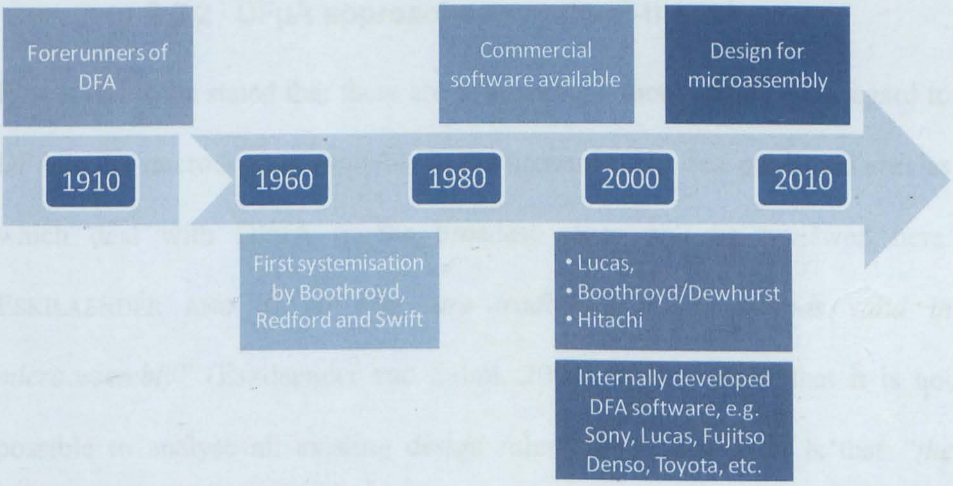

Figure 21: History and trends of DFA

The first systemisations were carried out in the 1960s by GEOFFREY BOOTHROYD, ALAN REDFORD and KEN SWIFT. Commercial software became available in the 1980s. The most common and widespread tools are the *Boothroyd Dewhurst DFA method*, the *Hitachi Assembleability Evaluation method*, and the *Lucas method*.[5] Companies such as Sony, GEC, Fujitso,

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[5] It is also known as *CSC design for assembly/manufacturing analysis*. The technique was first developed by Lucas Industries (Mei, 2000, Miles and Swift, 1998).

Denso, and Toyota developed for internal use DFA methods which were not made commercially available (Whitney, 2004). REDFORD AND CHAL provide a comprehensive review of DFA methods, including descriptions, comparisons, and classifications (Redford and Chal, 1994). A more recent review of DFA methods can be found in (Mei, 2000).

The increasing growth of MST (see section 1.1) and the challenges inherent in it (see section 2.4) raise the demand for microspecific DFA solutions. A general introduction to DFA and its history and relevance having been provided, the next section will examine the state-of-the-art in DFμA.

2.5.2 DFμA approaches – state-of-the-art

First it has to be stated that there are at present no monographs with regard to DFA in the microdomain available in the literature. The few published articles which deal with DFμA in the broadest sense will be reviewed here. ESKILAENDER AND SALMI ask *"are traditional DFA methods valid in microassembly"* (Eskilaender and Salmi, 2004). It is stressed that it is not possible to analyse all existing design rules. Their conclusion is that *"the majority of the design rules in macro- DFA are valid also for micro- DFA"* (Eskilaender and Salmi, 2004). But they also point out that *"some of the most critical parts of the assembly process, i.e. handling, feeding, gripping etc."* require updating or new design rules for the microdomain. For example, it is pointed out that the mechanical orientation of very small parts is difficult. In the main part of their article they discuss a limited number of design rules for a specific DFA-tool divided into two sections, the product level and the part level.

SALMI AND LEMPIAEINEN introduced the *"First steps in integrating micro-*

assembly features into industrially used DFA software" (Salmi and Lempiaeinen, 2006). The paper discusses the problems of microscale part manipulation and assembly. With a focus on DFA, two main difficulties are pointed out. The first issue is that the technical limitations due to part size are difficult to determine. Common practices might exist but the borders might always be pushed by a different technical solution. The second issue is the diversity of technical solutions and the rapid development of microassembly technologies (see section 2.1). Different technologies have different requirements regarding product design; therefore there are several possible strategies for solving an assembly problem, which makes it hard to formulate design rules. It is stated that the integration of the product design, process, and production equipment characteristics becomes even more important in the microworld. MARZ *ET AL.* underline this fact by observing that in microtechnology "[the] *function achievable by means of product design is rather technology-driven than subjected to requirements"* (Marz *et al.*, 2003).

The product design has implications on usable handling technologies and vice versa. This makes clear that a DFμA methodology should incorporate a way of making the match between required processes and existing processes.

Finally it has to be stated that SALMI/LEMPIAEINEN'S DFA-Tool is related only in a limited set of ways to microassembly and that *"the development of this tool is an iterative process"* (Salmi and Lempiaeinen, 2006).

MARZ *ET AL.* presented a *"Methodological investigation of the product development in microtechnology"* (Marz *et al.*, 2003). The paper deals with technology-related design rules, focussing mainly on machining. A key statement is that only in an *"all-embracing integration of technology, process* *and product development, material sciences and simulation optimal, innovative microsystems can be realised"* (Marz *et al.*, 2003). In order to deal with these multidisciplinary influences on the product design, rules have to be created and applied.

BULLEMA *ET AL.* investigate a common technology base for MST. To achieve their target they use a quality function deployment (QFD) -based method with the following key steps (Bullema *et al.*, 2003):

- A record of MST products and functional MST parts is made
- Functional application requirements are documented
- Functional requirements of the packaging and assembly requirements are derived
- Common denominators in technology are determined based on product analysis

About 60 MST products were analysed for their study, partly by practical disassembly and partly by literature review. The organising of products into groups was based on common packaging and interconnect technology, rather than on functions. The reason for which this method was employed is that their DFA approach sees the design of a microsystem as relying on proven interconnect and packaging technology. The objective is to design for cost effective producibility, not for the optimisation of functionality. Figure 22 shows the approach proposed by BULLEMA *ET AL.*

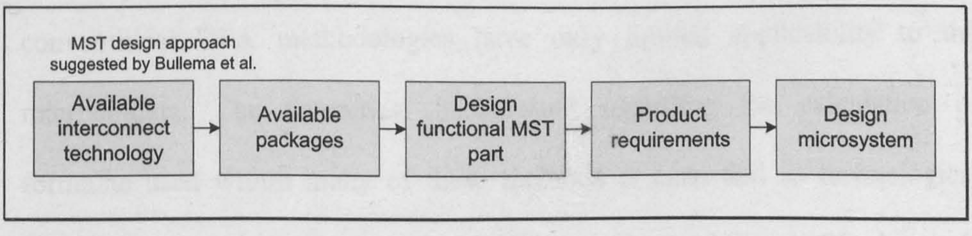

Figure 22: Design approach based on available solutions (BULLEMA *ET AL.*, 2003)

Their approach does not consider a trade-off between the product design and the selection of processes and very much relies on existing libraries. It might be questioned whether this provides a satisfactorily practical solution, since the neglecting of functional purposes can be understood as likely to compromise the search for good solutions. It is clear as well that considering product requirements only later in the product design stage may lead to a dramatic increase in costs (see section 2.2.1).

After reflecting on what is said in the presently limited amount of papers (no monographs available) on the topic of DFμA and the derivation of characteristics for the development of a DFμA methodology, it can be summarised that no adequate DFμA methodology has yet been provided.

Due to ongoing research and the enormous variety of assembly processes, the designer should be made aware of what is possible to realise a producible cost effective design. Naturally, commonly accepted DFA methods need to be analysed for applicability in the microdomain to utilise the findings in addressing the gap in DFμA knowledge.

2.5.3 Analysis of conventional DFA methods

'Conventional' here refers to common DFA methods, excluding the microspecific approaches described in the previous section. To emphasise the need for DFμA methodologies it is necessary to explain how and why conventional DFA methodologies have only limited applicability to the microdomain. The theoretical background regarding the calculation of formulae used within many of these methods is classified as technological knowledge, and the theoretical details have not been published (Ohashi *et al.*,

2002). Thus, this examination is restricted to the most common and widespread methods: the *Boothroyd Dewhurst DFA method,* the *Hitachi Assembleability Evaluation method,* and the *Lucas method.*

The Boothroyd Dewhurst DFA method (Boothroyd and Dewhurst, 1989)

This method is widely accepted in the research community in both industry and academia. The method starts out from an existing product design which is iteratively assessed and enhanced. It is based on the following two principles (Chan and Salustri, 2005a):

- The application of criteria to every component to establish whether it should be separate from all the other parts.
- Estimation of the handling and assembly time and cost for every part considering the appropriate assembly process.

The Boothroyd Dewhurst DFA method distinguishes between manual and automatic assembly (Figure 23). The evaluation in automatic assembly is determined with reference to the relative cost of the equipment needed to process the easiest or ideal design (Mei, 2000). Each part in the design is rated for the difficulty it presents to assembly in terms of movement, grasping, and orientation; this includes insertion and fastening difficulties. The materials and processes are selected and costs estimated. Trade-off decisions between reduction of parts and increased manufacturing cost can be made (Mei, 2000).

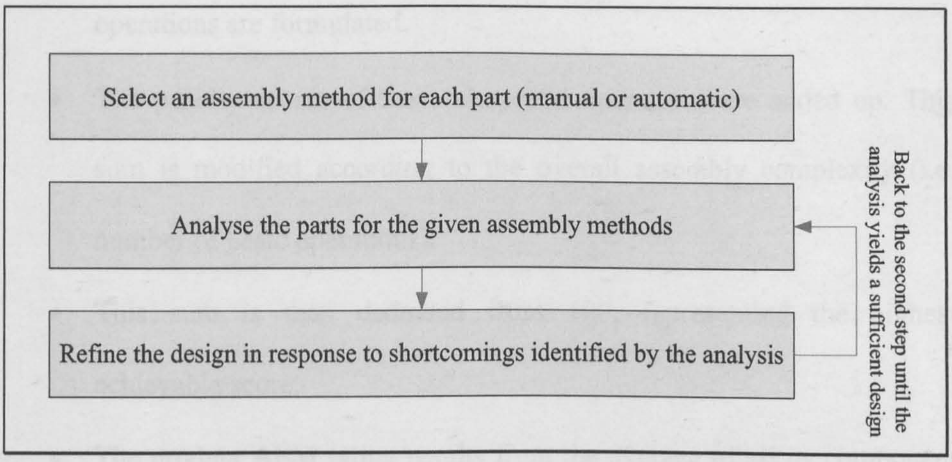

Figure 23: Process steps of the Boothroyd Dewhurst method (after Chan and Salustri, 2005a)

Part handling and insertion times are estimated with the help of tables and charts provided through time studies (Molloy *et al.*, 1998). These *"lookup tables"* (Chan and Salustri, 2005a) use two-digit codes that are based on components' sizes, weights, and geometric characteristics.

The Hitachi Assembleability Evaluation method

The *Hitachi Assembleability evaluation method* (AEM) is a tool developed by Hitachi (Ohashi *et al.*, 2002, Miyakawa and Ohashi, 1986). It uses the two criteria *'ease of assembly'* and *'estimated assembly cost'* to distinguish between designs (Molloy *et al.*, 1998).

For the AEM, assembly operations are categorised into approximately 20 elemental operations. The optimal operation is the *"downward attachment operation"* (Ohashi *et al.*, 2002), which is the standard basic element. A penalty score is attached to the other basic elements proportional to the difference of the element's average operation time from that of the standard element. The evaluation process takes place as follows:

- By choosing from the elemental operations the product's assembly operations are formulated.

- The penalty scores of these elemental operations are added up. This sum is modified according to the overall assembly complexity (i.e. number of basic operations).
- This sum is then deducted from 100, representing the highest achievable score.
- The product AEM rating results from the average of all its component scores.
- Based on the product's AEM score and the number of components the assembly time and cost are estimated.

The Lucas method

The Lucas method is based on three separate and sequential analyses intending to reduce part-count in the product (LUCAS, 1991). These are illustrated as part of the *assembly sequence flowchart* (ASF) in Figure 24. The analyses are based on a *point scale* describing the assembly difficulty.

In the *functional analysis* the product parts are examined for their function only, dividing them into groups *A* and *B*. Group A contains components that are essential to the product's function. The parts in group B are *not* directly necessary for the product's function, typically screws or locator pins. The number of parts in each group is represented by the figures A and B in the formula given used to calculate the efficiency of the design:

$$E_d = A/(A+B) \times 100\% \qquad (1)$$

The design efficiency in Lucas is applied to pre-screen a design alternative, whereas Boothroyd-Dewhurst relies on a ready available design (Chan and Salustri, 2005b). Generally, design efficiencies of above 60% are targeted.

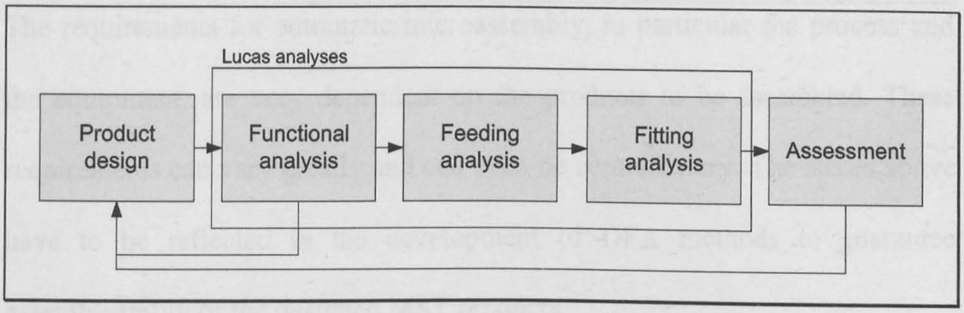

Figure 24: Layout of Lucas DFA method

The next step includes the *feeding analysis*, where both the component handling and insertion times are looked at. Feeding indices are defined for each individual part. Generally a part should be considered for redesign if its index is higher than 1.5. An overall feeding ratio is defined as follows:

Feeding ratio = (total feeding index) / (number of essential parts) (2)

The total feeding index is the sum of all the indices of every component, and the number of essential components is the value A from the functional analysis described above. A recommended value for the feeding ratio is around 2.5.

The *fitting index* is similar to the feeding analysis and a score of 1.5 is aimed for in each assembly whilst an overall fitting ratio of 2.5 is desirable:

Fitting Ratio = (Total fitting index) / (number of essential parts) (3)

The literature review has shown that new challenges arise due to increasing miniaturisation of parts and products (see section 2.4). For example, the fact that gravitational and inertial forces may become insignificant in the microworld has been identified as one of the key issues when transferring form macro- to microassembly. Furthermore, it has been outlined that microassembly is a fast moving and complex domain and that there are product design-related problems in determining suitable assembly processes for automatic microassembly (see section 2.4.3).

The requirements for automatic microassembly, in particular the process and the equipment, are very dependent on the products to be assembled. These requirements can vary greatly and can even be contradictory. The issues above have to be reflected in the development of DFA methods to guarantee assembleability of the designed MST products.

The literature has also reviewed key microassembly processes and the following main problems for the automation of the full process chain are identified:

- There is a need to further develop existing microasembly processes to cope with varying fabrication volumes, very tight tolerances, and specific physical challenges
- There is a lack of standardisation in the design of miniaturised products (particularly when interfacing with the macroworld)

These problems are not directly addressed through the development of the DFμA approach presented here. However the DFμA methodology can cater for better microproduct designs so that it can deal with the current state-of-the-art in microassembly, enabling a better transfer from research prototypes to industrial practice.

The literature review has clearly shown that DFA methods are at many points not applicable to the designing of microproducts. With the state-of-the-art in DFμA reviewed and assessed as insufficient, the next chapter deals with the research approach adopted to tackle the shortcomings of DFA with regard to the microdomain and thereby define the knowledge gaps to be addressed.

3 Research approach

The objective of this chapter is to clarify and describe the research approach employed here to ensure the scientifically accurate development of the DFμA methodology and its elements within the defined scope. First of all, the baseline for the research is defined (section 3.1), i.e. analysing the limitations of current DFA methods, identifying the knowledge gaps, and highlighting the contributions that the DFμA can be expected to make in academia and industry. Subsequently, the overall research methodology that is used to enable these knowledge contributions is described (section 3.2). The research approach is analysed and formulated with respect to generally accepted research theories and methodologies. A central feature of the development of the research approach was the definition of objectives in such a way that their completion guarantees the filling of the knowledge gaps and the realisation of the research aims.

3.1 Baseline definition

3.1.1 Limitations of current DFA methods

A general problem related to DFA methods is the fact that many design engineers believe taking assembly into account during the design process leads to the producing of a product which ultimately *performs* less well than the design engineer would have hoped (Whitney, 2004). In addition, their limited knowledge of assembly makes it difficult for them to design with assembleability in mind.

This is even more the case in microassembly where the optimisation of matching product requirements to process features and the lack of microspecific assembly guidelines are major issues.

The development of MST products is much more driven by trends within manufacturing and assembly process technology than is the case in conventional product design. As a matter of fact, microassembly, being one of the critical manufacturing processes in MST, is characterised by a large range of maturing handling, feeding, and joining processes which must be considered in DFμA approaches.

An overview of the shortcomings of current DFA methods based on relevant analyses that have been outlined in the literature review (particularly section 2.2 and 2.5) is summarised in Table 2. That table illustrates how this thesis will set about proposing developments to address these drawbacks. Points 1), 4), 5), 6), and 8) of Table 2 are addressed through the development of a *microassembly process capability model* (see Chapter 4) needed in order to facilitate the reflecting in the product design stage of the limits and possibilities of microassembly processes. At present, although these process characteristics *do* influence product development, the designer is not supported in selecting suitable microassembly processes. This can result in the worst-case scenario of having (literally) to go back to the drawing board, because assembly cannot be realised.

Table 2: Limitations of current DFA methods addressed by this thesis

	Limitations of current state-of-the-art in DFA	**Developments within this thesis advancing the current state-of-the-art**
1	Current DFA methods do not take essential characteristics of assembly processes into account (Mei, 2000)	Chapter 4 - Microassembly process capability model
2	DFA methods need to be improved to fit the conceptual design stage (Mei, 2000)	Chapter 5 - DFμA methodology Chapter 6 - DFμA guidelines
3	No generation of appropriate redesign suggestions (Mei, 2000)	Chapter 5 - DFμA methodology Chapter 6 - DFμA guidelines
4	The analysis of the product design should reflect the actual manufacturing concerns of the user and produce different results for different processes or equipment (Molloy *et al.*, 1998)	Chapter 4 - Microassembly process capability model
5	Product design analysis should relate design features with manufacturing features and processes (Molloy *et al.*, 1998)	Chapter 4 - Microassembly process capability model Chapter 5 - DFμA methodology
6	Current methods lack the possibility to capture manufacturing rules and decisions (Molloy *et al.*, 1998)	Chapter 4 - Microassembly process capability model Chapter 6 - DFμA guidelines
7	Lack of microassembly-specific rules (Ratchev and Turitto, 2008, Watty, 2006, Dimov *et al.*, 2006, Klaubert, 1998, Nelson *et al.*, 1998)	Chapter 6 - DFμA guidelines
8	Most DFA methods focus on assembly of products with part dimensions from a few millimetres up to several decimetres (Eskilaender and Salmi, 2004)	Chapter 4 - Microassembly process capability model Chapter 5 - DFμA methodology Chapter 6 - DFμA guidelines

It has been clearly outlined that commonly used DFA methods were not developed with the microworld in mind and are at many points not applicable to the designing of microproducts (see section 2.5). This can be illustrated by the fact that it is a key objective of those methods to restrict miniaturisation in order to secure greater ease of assembly. While this has benefits for conventional assembly; for microproducts, which *by definition* should become more miniaturised, it is plainly not a suitable approach.

It is therefore easy to recognise the crucial importance of developing the *procedural DFμA methodology*, addressing particularly points 2), 3), 5), and 8) displayed in Table 2. Nevertheless, some of the underlying methodological *concepts* of existing DFA approaches can still be valid and are utilised in this thesis, which takes into account the basic elements of the Boothroyd Dewhurst method (see Chapter 5).

The investigation of *microspecific guidelines* (see Chapter 6) supports the development of the DFμA methodology by specifically tackling points 2), 3), 6), 7), and 8). Such guidelines would be of enormous help, particularly to the inexperienced designer. For other manufacturing processes, such as milling or casting, and for the using of certain materials, e.g. injection moulding polymers (Sha *et al.*, 2007 , Goodship, 2004), guidelines of this kind represent the state-of-the-art. Approaches for the drawing up of guidelines exist as well in MST, for example for LIGA (Malek and Saile, 2004, Lessmoellmann, 1992) or micromechanical production processes (Vella *et al.*, 2007). Microassembly, then, can be seen as unusual in not having a set of domain-specific guidelines of this sort.

There is a lack of rules specifically defined for microassembly, although there is a general agreement of their importance in the literature (see Table 2).

3.1.2 Knowledge gap definition

Given below is a survey of major international studies carried out by renowned institutions, it serves to illustrate the continued lack of an appropriately rigorous and comprehensive DFμA methodology.

EHMANN *ET AL.* state in their study *"International Assessment of Research and Development in Micromanufacturing"* (Ehmann *et al.*, 2005) for the World Technology Evaluation Center Inc. (WTEC)[6] that design researchers have not yet addressed the field of non-lithography-based meso- and microscale parts. In defining the state-of-the-art of *"Design Theory and Process"* with a view to identifying the gaps presently existing, it is pointed out that:

- Little work has been done to *"develop general theories and approaches that could be used to design"* (Culpepper and Kurfess, 2005) micro- and mesoscale parts.
- Such *"General design theory and process work has yet to be addressed"* (Culpepper and Kurfess, 2005).
- It is necessary to generate designs compatible with available fabrication technologies.
- Rules have to be determined by research to enable designers to select suitable design-fabrication process combinations.

These issues were also addressed in a workshop on manufacturing

[6] The WTEC is a leading organisation in the USA in conducting international technology assessments by expert review.

technologies for integrated nano- to millimetre-sized systems held by the *US Defence Advanced Research Projects Agency* (*DARPA*) and the *US National Institute of Standards and Technology* (*NIST*). The workshop aimed at identifying key requirements for realising such systems and at recognising areas for innovative research to overcome barriers in integrating parts that are manufactured through various processes spanning from nano- to millimetre dimensions (Ehmann *et al.*, 2005, NIST, 1999). The intended purpose of that workshop was *"identifying key assembly process technologies that will enable more optimal system performance while conforming to schedule, quality, and affordability requirements"* (NIST, 1999). One result has been an elaboration on specific needs and research topics that are seen as essential for microassembly which explicitly underlines the necessity for a *"Theory of Design for Micro-Assembly"* (NIST, 1999). It is stated that there are currently "*no good theoretical foundations for guidance and no widely available infrastructure technologies to draw on*" (ibid.). HSU emphasises the validity of these needs worked out by the DARPA/NIST workshop by calling them a *"great challenge"* (Hsu, 2005) to engineers. Furthermore he specifically mentions the need for DFμA tools.

HESSELBACH *ET AL.* studied the international state-of-the-art of microproduction technology with regard to its potentials and deficiencies (Hesselbach and Raatz, 2002). They point out that it is difficult to give recommendations for future research and developments in the area of automatic microassembly because process requirements and handling equipment depend strongly on the product to be assembled (Hesselbach and Raatz, 2002).

Knowledge gaps

Based on the relevant needs in the area of microassembly, the knowledge gaps are identified as follows:

- **There is no sufficient DFμA methodology available at present. Trying to employ conventional DFA methods in the microworld is unsatisfactory since those methods were not designed to accommodate the domain-specific challenges arising in microassembly.**
- **Design rules and guidelines that are focused on the microworld and its specific challenges are needed.**
- **A structured approach is needed to support designers' decision-making during the development process of MST products.**
- **Microassembly process features need to be considered in early design stages. This is extremely important due to fact that the nature of the parts to be assembled, and specifically their very small dimensions, will bear on the assembly process in ways (and to extents) that are not seen in conventional assembly .**
- **There is a need for support in the selection of suitable microassembly processes by considering process-related requirements as well as offering qualtitative cost indications (best match between product requirements and process features).**

These knowledge gaps will be addressed by developments which extend the existing body of knowledge of DFA and DFμA. These developments comprise a microassembly process capability model, a procedural DFμA methodology, and a model for microworld-related guidelines (see Figure 25).

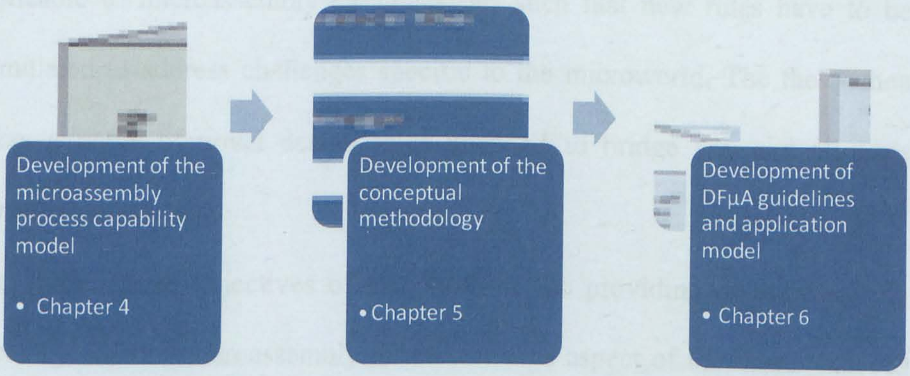

Figure 25: Interrelation of key developments extending the existing body of knowledge of DFA and DFμA

3.1.3 Intended contribution to academia and industry

In general terms, *scientific contribution* to a topic can be characterised as extending the existing knowledge in the field of that topic (Svensson, 2003). The work described in this thesis makes a number of contributions to knowledge in the field. This section gives a summary of the contributions it is expected to make to both academic and industry, the providing of which will as well serve to clarify the research methodology definition (see section 3.2).

Contribution to academia

The investigation of the field of DFA provided here offers novel input to the existing corpus of research, and particularly with regard to the area of microassembly. Results of this theoretical analysis can form the basis for future research. Elements of the literature review can be used as source material for others investigating the area.

This thesis collates existing design rules, and shows where and how conventional DFA rules can be transferred to or adapted for the microdomain. Still more importantly, it demonstrates where existing DFA methods are *not* applicable to microassembly circumstances such that new rules have to be formulated to address challenges specific to the microworld. The thesis then offers a range of novel design rules intended to bridge any and all gaps identified as existing.

One of the major objectives of this thesis is the providing of assistance in selecting suitable microassembly processes. This aspect of the thesis exceeds the scope of conventional DFA methods, which seek only to optimise the assembleability. Optimised product design and microassembly process selection is supported by analysing microassembly process characteristics and providing a methodology which enables their consideration early in the product design stage.

The key *contributions to the academic community* can be summarised as follows:

- Novel inputs to the research fields DFM and DFA
- Development and collection of microassembly-specific design rules
- Development of a general framework to capture microassembly process characteristics
- Support of microassembly process selection
- Consideration of microassembly process characteristics early in the product design stage
- Decision support of assembly process selection

Contribution to industry

> *"In one way or another, every MST application requires a dedicated solution"* (Leach *et al.*, 2003).

MST product design draws on knowledge from different fields, including optics, mechanics, magnetics, chemistry, and biology. For industry this means that specialists from various disciplines have to work together. The need to integrate a diverse range of fields requires a knowledge-based approach to the design and assembly of microproducts.

In an industrial context, the proposed DFμA approach, focussing on product design and process selection, can have an immediate impact by reducing the need for *'communication/contacts', 'waiting for information and decisions', and 'planning'* (see Figure 11). This is done by guiding the design engineers and providing them with assembly process-related information, which frees resources of time, money, and manpower for more productive use. In addition, the DFμA methodology can have a significant impact on the product's success by considering later stages of the product's lifecycle in the early stages of the technical product design.

The consideration of microassembly process-related information in the design stage contributes to another important aspect of industrial microproduct design: the requirement for high product reliability, which should be addressed before prototyping and production (Richardson *et al.*, 2006). As well as the advantages outlined above, the adopting of the DFμA methodology in industry confers the following significant benefits:

- Increasing the transfer of microproduct prototypes from the research laboratory to market (industrial production)
- Availability of microproduct-specific design rules
- Selection and evaluation of possible assembly processes
- Shorter time to market for microproducts

3.2 Overall research methodology

Following the baseline definition in 3.1, this section explains the overall methodology applied to carry out the research presented here. Therefore research is described as *"a mediator between reality and scientific knowledge"* (Svensson, 2003). Figure 26 illustrates how research observes reality whilst being based on existing scientific knowledge. New scientific knowledge is derived from these observations.

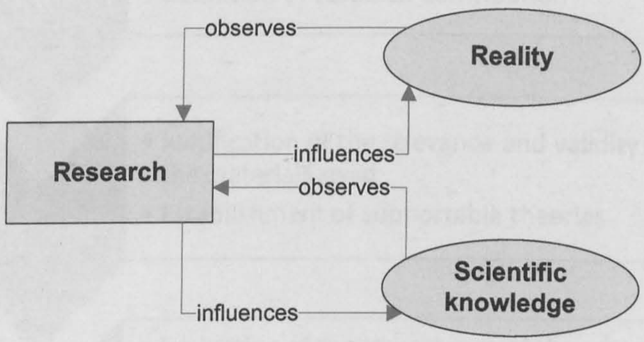

Figure 26: Research between reality and theory (adapted from Svensson, 2003)

For the complex area of engineering design (involving elements such as people, tools, processes, organisations, and their environments) *scientific knowledge* can be defined as *"as socially justifiable belief"* (Seepersad *et al.*, 2006). Accordingly design research aims at "*increasing the understanding of the phenomena of design in all its complexity*" (ibid.). Scientific work in the area of design includes "[the] *development and validation of knowledge, methods, and tools to improve the design process*" (ibid.). To ensure a proper scientific rigour, a number of research approaches have been assessed for their suitability to a research study in the field of engineering design. Following that process of assessment, it has been decided that this thesis should adopt the research approach suggested by PUGH AND PHILLIPS, who define four theoretical areas that need to be addressed in carrying out scientific research (see Figure 27): *background theory, focal theory, data theory, and contribution* (Phillips and Pugh, 2005).

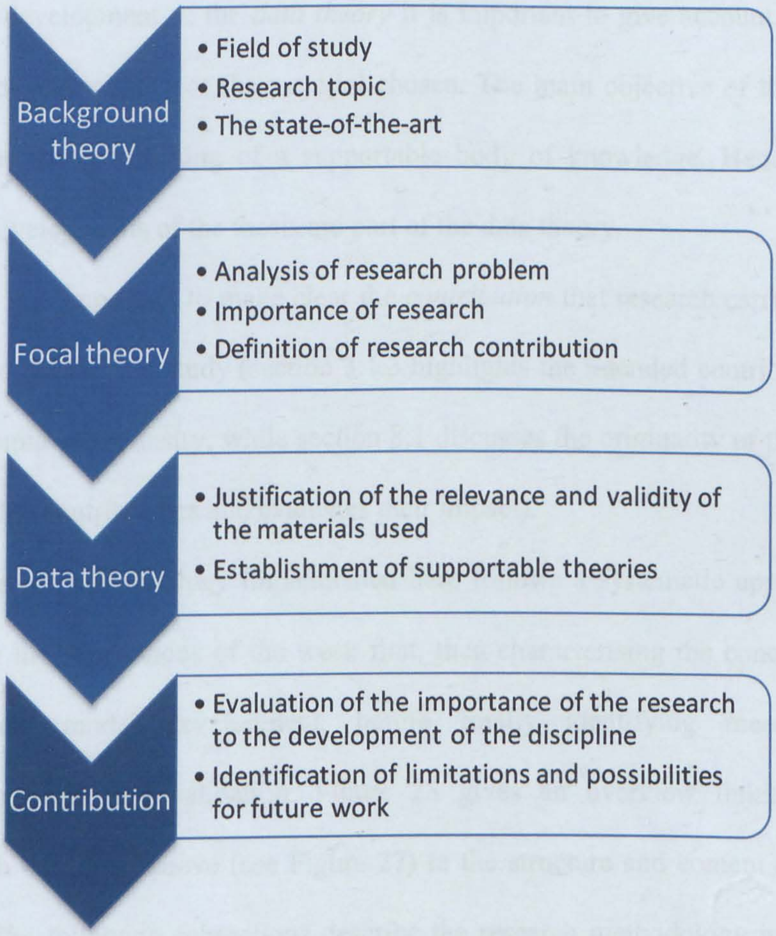

Figure 27: Research methodology – analytical constructs covered by the thesis (based on Phillips and Pugh, 2005)

The *background theory* introduces the area of study, defines the research scope and topic, and reviews the state-of-the-art in the field. In this thesis, this is done chiefly in chapters 1 and 2, which describe the scope and importance of the research, and analyse prior research and current developments related to the areas of DFA and DFμA.

The chapters on background theory lead to the defining of the knowledge gaps in the field (see section 3.1.2), which is part of the *focal theory*: essentially, describing what is being researched and why. This consists in analysing the research problem, underlining the significance of the research, and defining the research contribution (see sections 3.1.1 and 3.1.3).

For the development of the *data theory* it is important to give account of the relevance and validity of the material chosen. The main objective of the data theory is the establishing of a supportable body of knowledge. Hence, the major developments of the thesis are part of the data theory.

Finally, it is important to make clear the *contribution* that research carried out makes to the field of study (section 3.1.3 highlights the intended contributions to academia and industry, while section 8.1 discusses the originality of the key knowledge contributions and evaluates their impact).

The research methodology implemented here follows a systematic approach: defining the foundations of the work first, then characterising the conceptual work and model development, before finally identifying means of implementation and validation. Figure 28 gives an overview linking the approach described above (see Figure 27) to the structure and content of this thesis. The following subsections describe the research methodology in more detail, explicitly outlining the *foundations of the work* (see section 3.2.1), the *conceptual work and model development* (see section 3.2.2), and the *implementation and validation* (see section 3.2.3).

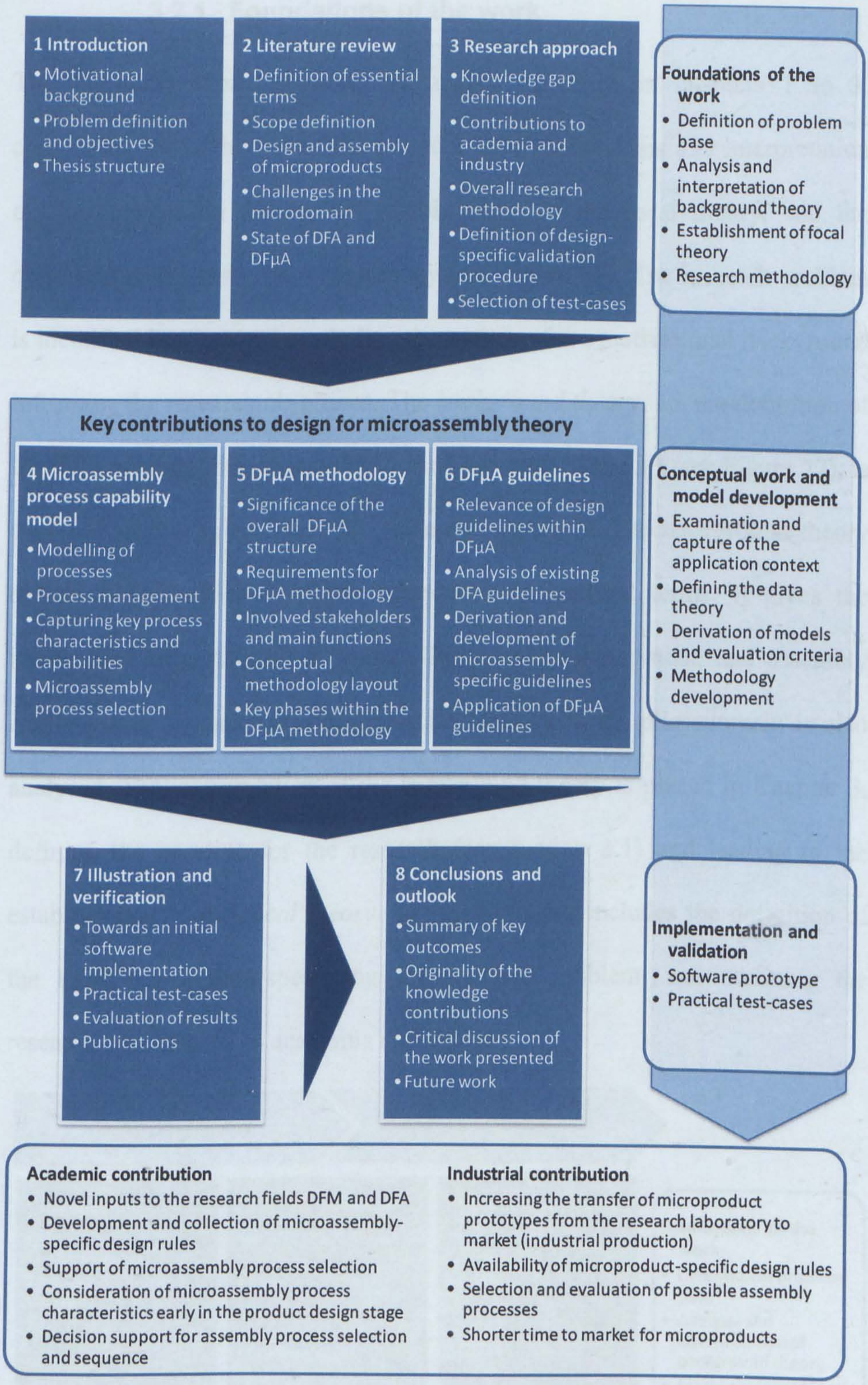

Figure 28: Research methodology – in the context of the structure of the thesis

3.2.1 Foundations of the work

The foundations of the work are mainly described in chapters 1 to 3, comprising the definition of the problem base, the analysis and interpretation of the background theory, the establishment of the focal theory, and the definition of the research methodology (see Figure 29). The research problem is identified in Chapter 1, including the outline of the motivational background informing the research objectives. The *background theory*, i.e. the definition of the field of study, the research topic, and the state-of-the-art (see Figure 27), is analysed mainly in the literature review (Chapter 2). The background theory defines both the scope of the thesis and its essential terms. It gives the background information on product design and development, and assembly challenges in the microworld. The state of DFA in the microdomain is also analysed. The interpretation of the background theory is placed in Chapter 3, defining the baseline for the research (see section 3.1) and leading to the establishment of the *focal theory*. The focal theory includes the definition of the knowledge gaps, specifying the research problem, and outlining the research contribution to academia and industry.

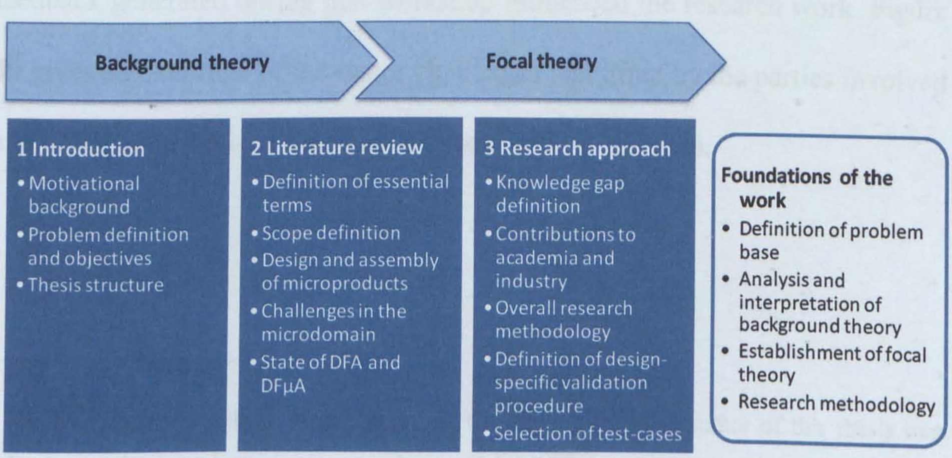

Figure 29: Foundations of work – establishing background and focal theory

The overall research methodology, being as well part of *the foundations for this work,* is defined in section 3.2. It describes the scientific approach adopted to carry out the research and also identifies possible verification routes.

In order to guarantee the relevance of the work and to capture industrial needs, a two day workshop *"Assembly in the production of microproducts"*[7] was held at Nottingham University in the early stages of the research process. 20 participants from leading international research institutions, both academic and industrial, presented and discussed their views on the following topics:

- Progress in the design of microproducts: how to support the designer in process selection and product design
- Integration of innovative manufacturing processes to reduce the need for assembly
- Simulation tools in micromanufacturing and -assembly

While all three topics are related to the issues addressed in this thesis, it was the first of them, the discussion regarding microproduct design, that was of key interest. The principle of the DFμA methodology was discussed, and ideas and feedback generated during that workshop influenced the research work. Figure 30 gives an overview of the major challenges identified by the parties involved and of the contributions they hoped to see made to the field.

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[7] The workshop was held in Nottingham on 16-17 July 2007. The author of this thesis was actively involved in designing, organising, and leading the workshop. The workshop was structured in a way that involves the partners actively, splitting them into small groups discussing each of the topics during the two days.

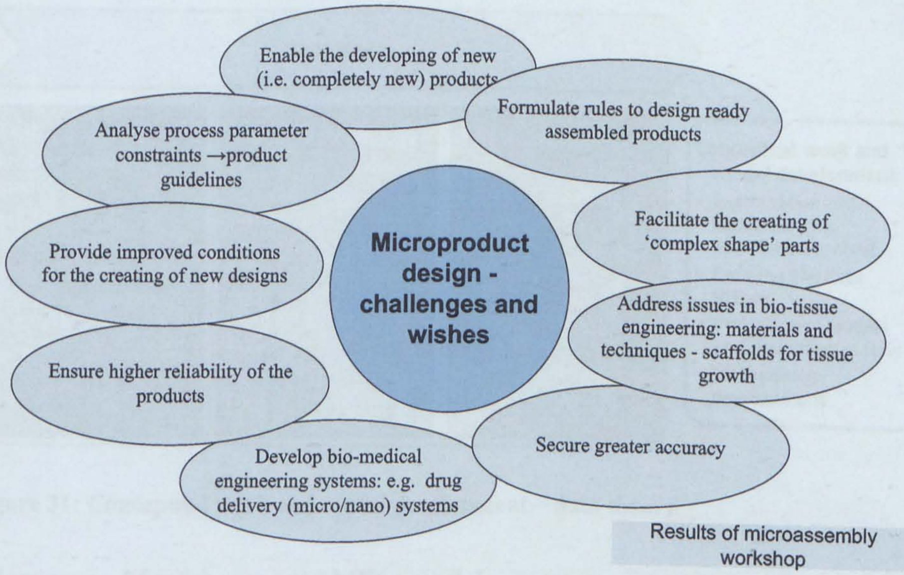

Figure 30: Desired breakthroughs and identified challenges in microproduct design

3.2.2 Conceptual work and model development

The *conceptual work and model development* together provide the key knowledge contributions to the field of *DFμA*. The applicational context is examined here, and the data theory based on derived models and methodologies is defined (see Figure 31). The most important parts of the conceptual work are the development of the *microassembly process capability model* (Chapter 4), *the DFμA methodology structure* (Chapter 5), and *the DFμA guidelines* (Chapter 6). These developments are based on chapters 1 to 3, representing the foundations of the work.

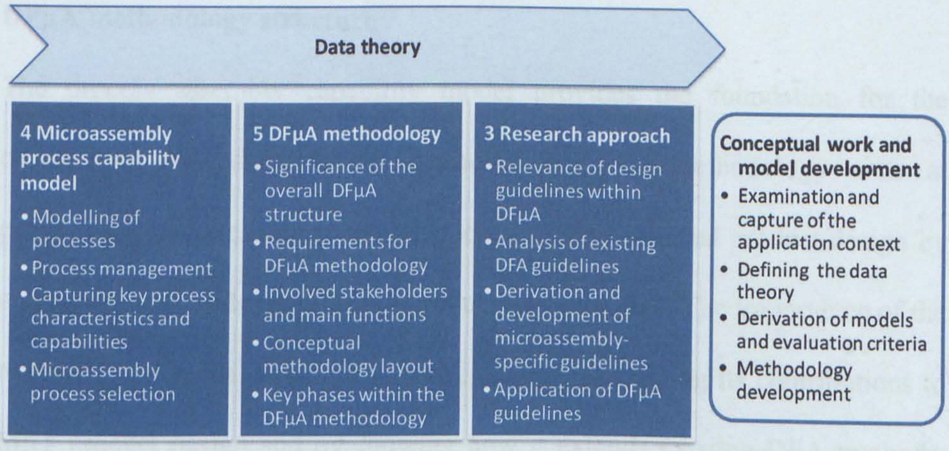

Figure 31: Conceptual work and model development – data theory

Microassembly process capability model

In order to develop a microassembly process capability model it is essential first to review the fundamentals in process modelling. Doing so allows that the basics can be captured and as well makes it possible to examine the relevance that process modelling and planning has in research and industrial applications. These form the basis for the actual development of the *Cube Model for Microassembly Process Capabilities*, comprising two stages:

- Rough planning and
- Detailed planning

Two research strands form the basis for the Cube Model:

- Process selection and
- Process characterisation

For the process selection strand a strategy is developed and assembly processes are classified. The process characterisation strand deals with process characteristics and means of capturing them. The key characteristics of the microassembly processes *handling, joining, and feeding* are defined.

DFμA methodology structure

The process assembly capability model provides the foundation for the overarching procedural DFμA methodology. That methodology aims at providing a flexible framework for microassembly-oriented product design by connecting and bridging different product design stages. The importance of the method's conceptual structure is highlighted by describing its contributions to MST product design and by showing how it extends existing DFA methods. The actual development process of the DFμA methodology is described on that basis. In the providing of that description, generally applicable requirements, involved stakeholders, and main functions are defined using the *unified modelling language* (UML). This leads on to the definition of the layout of the DFμA methodology, the key phases of which reach from conceptual product design specification over product analysis to process-product analysis and microassembly process selection.

DFμA guidelines

The application context for DFμA guidelines is examined by outlining the relevance of design guidelines within the overall DFμA methodology. The formulation of microassembly-specific guidelines is based on the analysis of microassembly processes as carried out in the literature review. A general approach to DFμA guideline development is developed, and this forms the basis for the analysis and adaptation of existing guidelines, and the generating of completely new guidelines where the existing ones are identified as inadequate or inapplicable. Finally a method for the application of these guidelines within the DFμA methodology and the wider MST product design theory is defined.

3.2.3 Implementation

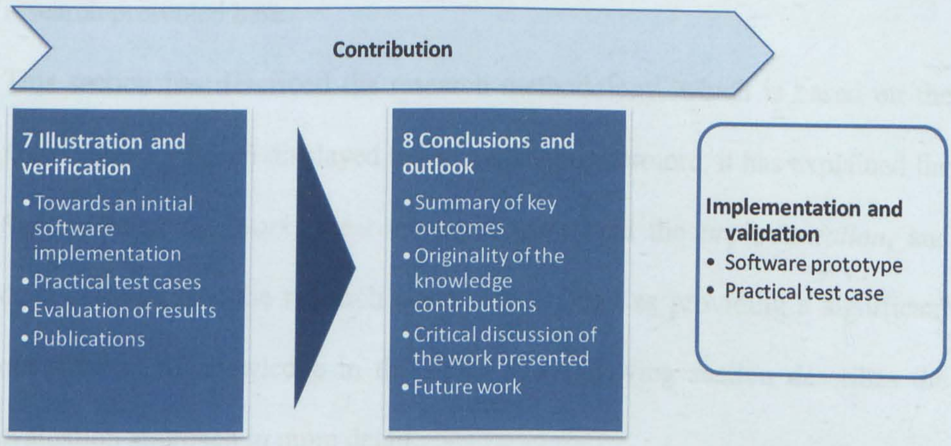

Figure 32: Implementation and validation – contribution

To illustrate the contributions to academia and industry, the developed models and methodologies are implemented in an initial software prototype and applied to selected test cases. The practical test cases serve the purpose of verifying the applicability of the key developments, namely the microassembly process capability model, the DFμA methodology, and the DFμA guidelines. This *illustration and verification* takes place in Chapter 7. The software environment is described by displaying the process characterisation application frontend and the process selection interface. Two test cases are chosen based on specific requirements (the decision-making process governing the selection of the test cases is described in section 3.3.2):

- Test case 1 – Micro-/Nanomeasurement device
- Test case 2 – Minifluidics device

The outcomes of the test cases are thoroughly examined and evaluated. The evaluating of these outcomes forms the basis for the concluding of the thesis (see Chapter 8). The conclusion summarises the key outcomes, critically discusses both the work presented and the originality of the knowledge contributions made, and outlines possibilities for future work based on the research presented here.

This section has described the research methodology, which is based on the *four stages approach* displayed in Figure 27. Furthermore, it has explained the *foundation of the work*, the *conceptual work*, and the *implementation*, and demonstrated how the research can be understood as providing a significant contribution to knowledge in the field. The following section describes the evaluation approach in more detail.

3.3 Evaluation approach

Evaluation methods are not 'one size fits all'. They have to be chosen with care, according to the nature of the subject studied and theories used (Svensson, 2003). The following subsections describe different verification and validation routes and explain the basis on which the test cases were selected. These inform the systematic approach adopted for the evaluating of the work carried out.

3.3.1 Verification and validation routes

> *"Due to the open nature of design method synthesis where knowledge is associated with heuristics and non precise representations (...)* ***knowledge validation becomes a process of building confidence in its usefulness*** *with respect to a purpose" (Seepersad et al., 2006).*

Verification and validation constitute the core of any evaluation. According to BALCI, *verification* deals with the question of whether an entity has been created in the *right way*, whereas *validation* asks whether the *right entity* has been created (Balci, 2003). In other words, the first examines the *accuracy* and the *predictive and explanatory capabilities* of the theories, methods, and models under consideration, while the second determines their *relevance and significance* (Warell, 2001).

A *design process* consists in large part of decision-making, particularly the identifying of options and their optimal selection (Shupe *et al.*, 1988, Hazzelrigg, 1998). It is important, therefore, that the DFμA methodology should satisfy criteria identified as characterising well developed decision-support methodologies. The model to be employed for conducting this evaluation is that proposed by OLEWNIK AND LEWIS who state that for a decision support methodology to be valid, it has to (Olewnik and Lewis, 2005):

- Be *logical*: The results have to be rational and to make sense. This can be examined by using test cases. The methodologies should be constructed in such a way that future changes can be accommodated while maintaining a logical coherence.
- Use *meaningful, reliable information*. The information utilised in the models need to consider interdependencies between system variables and has to come from reliable sources.
- *Be objective*. The methodology should not impose certain solutions because that could influence the design objectives. Simply put, the designer must be able to define his own preferences.

The research work carried out will be both illustrated and verified through practical case studies. According to MØRUP, such an *application of design tools and methods to a real design problem is the only way of directly proving them* (Mørup, 1993). In the literature there are many different definitions of case studies with diverse centres of attention and different facets. The purpose of the case study as a scientific method can be summarised in short as enabling investigators to *"retain the holistic and meaningful characteristics of real-life events"* (Yin, 2003). The application of case studies is a widespread research strategy used in various fields such as psychology, sociology, political science (Gilgun, 1994), business (Ghauri and Grønhaug, 2002) and economics (Yin, 2003). In addition, a broad range of case studies can be found in the context of engineering, where they are used chiefly for evaluation purposes. YIN states that they have a *"distinct place in evaluation" (Yin, 2003)*, because of their being able to demonstrate specific subjects in a descriptive way. This thesis employs two practical test cases for such evaluative purposes. Their characteristics and the reasoning behind their selection are described in the following section.

3.3.2 Test case selection

The DFμA methodology is applied to carefully selected areas of microassembly in order to gather an understanding of transferability and applicability to industrial practice. A further benefit attaching to the using of test cases is that it allows for the identifying of flaws in the approach being examined. The object of this section is to outline the justification for the selection of the test cases to be employed here. This will be done by explaining the importance to industry of the fields from which they are drawn, and by identifying the microassembly challenges the test cases present. The two test cases (Test case 1: Micro-/Nanomeasurement device, Test case 2: Minifluidics device) used to test the proposed DFμA methodology are described as follows:

Need and relevance of test case 1 - Micro-/Nanomeasurement device

The industrial area of metrology has been chosen because "*measurement underpins manufacturing technology*" (Leach *et al.*, 2000). In addition, an improvement in metrology equipment is required in response to the ongoing trend toward miniaturisation, in order to enable quality assurance for emerging three-dimensional products with nanometre scale features. Most of the devices used for microprocess examination originate from the macroworld and do not meet the microtechnology requirements. The downscaling of macroworld methods and techniques for quality control is problematic, because experiences and results cannot simply be transferred into the microdomain. For instance, aspects related to resolution, measuring range, or image quality all place limits on the applicability of these methods in the microworld (Pfeifer et al., 2001). However, the delivery of microproducts with nanometre scale features needs to be supported by reliable metrology (Leach *et al.*, 2000). Figure 2 gives a schematic overview of micrometrology and identifies four tasks that micrometrology has to perform: material testing, completeness checking, dimension and position measurement, and functional testing. These tasks are mainly performed on three different kinds of components: electronic components, optical components, and mechanical components. PFEIFFER *ET AL.* state that up to 90% of the necessary measurement jobs can be categorised as *dimension and position measurement* (Pfeifer *et al.*, 2001).

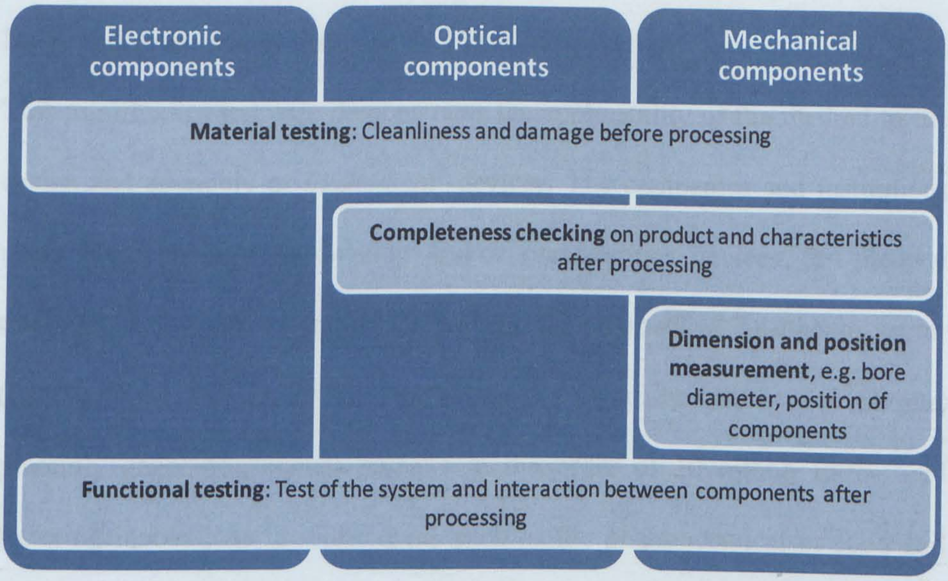

Figure 33: Measurement tasks in microtechnology (adapted, Pfeifer *et al.*, 2001)

The validation chapter describes in greater detail the measurement device which will facilitate in the key area of dimension and position measurement the achieving of the improved accuracies increasingly demanded by industry (see section 7.2). The case study deals with the stylus assembly for a state-of-the-art coordinate-measuring machine (CMM)[8] which is characterised by extremely rigid and challenging requirements. It demonstrates how the DFμA methodology influences the design of the parts to be assembled and enables the selection of appropriate assembly equipment. The assembly system and processes implemented and their validation are then described and illustrated (see section 7.2). In this way, it can be clearly demonstrated that and how the DFμA methodology facilitates improvements in the product design process.

[8] A CMM is a programmable instrument that is employed to measure dimensional data for various manufactured parts. Measuring a component using a CMM is realised by moving a touch probe to a range of points on the component's surface and calculating the position of the probe at each point via the machine scales. CMMs have three or more measurement axes, typically linear or rotary or both. The measurement axes are arranged in series so that a unique combination of their positions defines a single point in space (Tietje et al., 2008).

Need and relevance of test case 2 - Minifluidics device

This minifluidics test case demonstrates the applicability of the method to the design and assembly of *biomedical*[9] devices. The companies and institutions using biotechnology to develop and/or manufacture devices for medical treatment constitute an important part of the biomedical healthcare sector (EMCC, 2007, OECD, 2005). That sector is a significant industry in Europe, presently generating annual revenue in the order of 10 billion Euros, and fostering innovations in wider areas such as the pharmaceutical or food and beverage production (EMCC, 2006). In the UK, the biomedical sector is becoming an increasingly important industrial area, due to the medical demands attending the country's having an aging population. It represents a fast growing market in the developed world, with particularly high growth rates in the UK (Ratchev and Hirani, 2006). Furthermore, many products developed for this market are characterised by an ongoing trend of miniaturisation and functional integration, and by complex environmental constraints necessitating cross-disciplinary knowledge. Additional requirements such as biocompatibility, high reliability, tight tolerances, cleanliness, and governmental regulations make the biomedical sector one of the most complex industrial areas for microassembly applications, and therefore a challenging test case for the verifying of the DFμA methodology.

Within the biomedical sector micro- and minifluidics technology plays an important role in significantly altering procedures for various biological

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[9] The term *biomedical* refers to biotechnology-derived medical devices and products that are mainly acquired for the medical sector (EMCC, 2007).

analyses (Beebe *et al.*, 2002). Microfluidics technologies are used for 2D-lab-on-a-chip applications such as blood analysis or DNA analysis because they enable the integration of detection, sample preparation and analysis on a single chip. The selected test case is a minifluidics device which is characterised by these demanding functional and assembly requirements. In addition to the problems mentioned above, the device is designed three-dimensionally in order to enhance possible functionalities and to impose still stricter testing conditions on the DFμA methodology by requiring it to prove its applicability to 3D MST products.

First, this chapter gave an overview of the baseline definition for the research carried out. The gaps within existing DFμA knowledge have been clearly highlighted, limitations of current DFA methods have been summarised, and the knowledge gaps to be addressed have been described in detail. It has been shown that DFμA can be expected to make significant contributions to academia and industry.

Also defined was the research approach employed here to ensure both the scientifically accurate development of the DFμA methodology and the appropriate addressing of the knowledge gaps. The research approach has been formulated with reference to generally accepted methodologies while considering specific requirements resulting from the area of engineering design.

Finally, it has been explained that the models and methodologies will be demonstrated and verified through pilot-applications and test cases.

4 Microassembly process capability model

"Assembly is the least understood of manufacturing processes because people have always done it, people cannot explain how they do it, it is complex at the microlevel, it is complex at the macrolevel, and serious study of it began only recently (Whitney, 2004)."

This chapter describes the development of the microassembly process capability model. The model is a core component of the DFμA approach, forming the basis for capturing the characteristics of microassembly processes. The modelling of microassembly processes, particularly their capabilities, addresses the lack of understanding in the area of assembly-related research (see quotation). The advancement of microassembly technology and increasing complexity of products, especially in the microdomain, demands a systematic approach for the modelling of microassembly process capabilities.

The process capability model is needed to enable matching between microparts' design and the processes used to assemble them. It provides the designer with knowledge about the microassembly process domain that can usefully be considered in the conceptual design stage so as to avoid the need for costly and time consuming design reworking further into the process. Furthermore, it forms the basis for selecting assembly processes.

Pre-existing models cannot be used or extended for the purpose of the work presented here, for at least two reasons. First, as described above, the research area of assembly has until recently been neglected, and there are therefore no models available that meet the requirements of the DFμA methodology.

Second, the microassembly process capability model demands a microspecific solution, making it still more difficult, if not actually impossible, to extend existing models.

The need for an *ab initio* approach results from the technological and economic circumstances imposed by the microdomain, as discussed in the literature review. What is further true is that the microassembly capability model is intended to form the basis for a new DFμA methodology, such custom-making assures usability in a comprehensive approach tackling the current gaps in DFμA.

This chapter is structured as follows: first, it is fundamental for the development of a process model to discuss the basics in process modelling and to define the terms of reference. The importance of process planning as a whole within the production of microproducts is analysed (section 4.1). Second, the actual *microassembly process capability model* is introduced in section 4.2, where the purpose of the cube model and its structure are also discussed.

The two key parts of the cube model are explained in sections 4.3 and 4.4, describing the *process selection element*, including a process selection strategy and structured grouping of assembly processes, and the *process characterisation element*, representing the fundamental layer of the model. The process characterisation element explains how the microassembly process characteristics are captured and the data represented.

4.1 Fundamentals in process modelling

Before introducing the actual process capability model, the relevance of modelling processes and basics in process planning need to be discussed. This is done in the following two subsections.

4.1.1 Relevance of modelling processes

In general, process management describes the organisational and planning measures that aim at optimising the processes to be employed. The development of the manufacturing processes should be planned parallel to the product design stages in order to prepare for production and optimise the product's design relative to manufacturing conditions and limitations (see section 2.2). To guarantee a company's competitiveness, processes need to be (Bossmann, 2007):

- *Effective*, i.e. the specified objectives and tasks need to be fulfilled according to the requirements
- *Efficient*, i.e. the tasks need to be fulfilled by a minimum effort
- *Traceable and controllable*, i.e. the people responsible for the process need to be aware of the process state at any time and be able to correct it if necessary
- *Adaptable/adjustable*, i.e. it needs to be possible to respond to potential changes in the process environment

The *International Organisation for Standardisation* (ISO) defines a process as *"a set of interrelated resources and activities that transform inputs into outputs"* (ISO, 1994). For this thesis the inputs are product requirements, material and electricity, design, and DFμA guidelines, which collectively are converted into the output that is microproducts. Figure 34 illustrates the process by which the inputs are transformed into outputs using resources and activities.

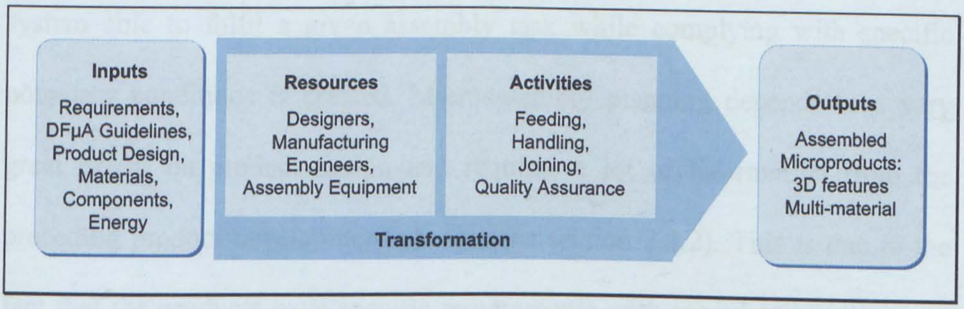

Figure 34: Microproduct assembly process

4.1.2 Process planning

Planning is generally understood as anticipating future actions by exploring different choices and deciding on the optimum solution. Planning of production systems and processes is seen as essential because of its high impact on the cost effectiveness of companies' products. Process planning in particular is a very difficult activity, depending heavily on the experience and domain knowledge of the process planner. In the microdomain the need for planning is growing due to the increasing complexity of the products and production facilities. Because of this, methods to decrease the process planning development time are crucial for the manufacturers of microproducts to enhance their competitiveness. So far, efforts to automate assembly process planning have been widely ineffective, such that it remains a manual task (Arnold *et al.*, 2004). Previous attempts to automate assembly planning were hampered by the need to process vast amounts of geometrical and technical information, particularly in the detailed planning phase that deals with the actual assembly operations (Bley and Fox, 1994).

The overall objectives of assembly process planning are to establish the conditions for cost-effective assembly, to investigate the resources required, and to ensure the efficient use of equipment. That is to say, a technological system able to fulfil a given assembly task while complying with specific boundary conditions is created. Microassembly planning depends to a very great extent on product design and requires a lot of information from the preceding product development phases (see section 2.2.2). This is due to the fact that the products have specific requirements with regard to handling and joining, but also because its components need to be stored, transported to the workplace, and fed to the machines. The complexity of the process as described here makes clear the need for a structured approach to support process planning in the area of microassembly. The following sections outline the design of a microassembly process capability model, which is one of the key elements of this thesis.

4.2 Cube model for microassembly process capabilities

Models in general aim at representing systems or processes with reference to certain questions or problems. A model is a physical or mathematical system, describing the problem-relevant characteristics of the real system to be examined. Specific real-world details are reduced by abstraction to the relevant elements. In summary, models serve the purpose of illustrating details and aspects of real-world circumstances (DIN, 1994).

The model presented here is structured as a cube consisting of several layers (see Figure 35). The top layers represent strategic aspects of the product and assembly planning, focussing on the enterprise and assembly line level (*rough planning*). The bottom layers deal with issues related to more *detailed planning*, such as process selection on workstation level and technology characterisation on equipment module level. The approach taken looks specifically at the dynamic area of microassembly, which is currently characterised by a lack of standardisation.

The microassembly capability model can be characterised as novel because it constitutes the first attempt made at providing a framework for capturing of microassembly characteristics. Currently OEM provide information *ad hoc* (not following a unified structure or framework), making it extremely difficult for the designer to consider microassembly process characteristics in the design phases of microproducts. Furthermore, such a model can make the equipment selection significantly easier.

Moreover, it is part of a holistic DFμA approach developed to overcome the currently existing bottleneck when transferring research prototype to commercially produced product.

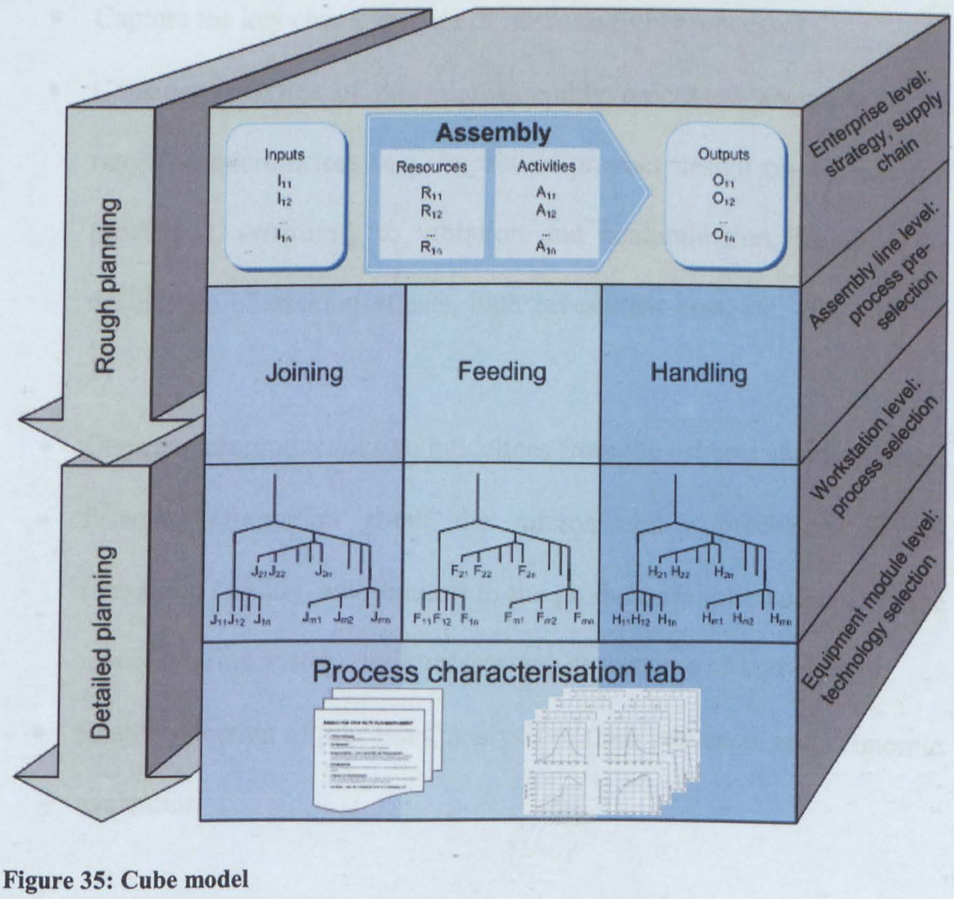

Figure 35: Cube model

The following subsections describe in more detail the purpose of the model (section 4.2.1), and the procedures of rough and detailed planning as represented by the cube (sections 4.2.2 and 4.2.3).

4.2.1 Purpose of the Cube Model

The overall objective of the model is to support the integration of product and process design, so that it can be utilised for the procedural DFμA structure (see Chapter 5). Assembly processes need to be designed to perform specific tasks. Presenting the processes in a model is important because it serves to simplify the complexity of those processes and to facilitate standardisation, both of which are necessary for the purposes of information retrieval. Moreover, such a model forms the basis for a possible software implementation. The development of the microassembly process model is essential in order to:

- Capture the key characteristics of microassembly processes
- Consider specifics of the microassembly processes: accuracy in the range of micrometres (e.g. impact of product design on accuracy of processes), sensitivity to vibration and contamination, fragility, the occurrence of sticking effects, high investment cost, etc. (see Chapter 2)
- Derive microproduct design guidelines from the process characteristics
- Provide information about the microassembly processes domain (handling, feeding, and joining) to the product designer and also to the manufacturing system designer (serving as a source of knowledge)
- Enable selection of processes, analysis of their sequence, and economic evaluation

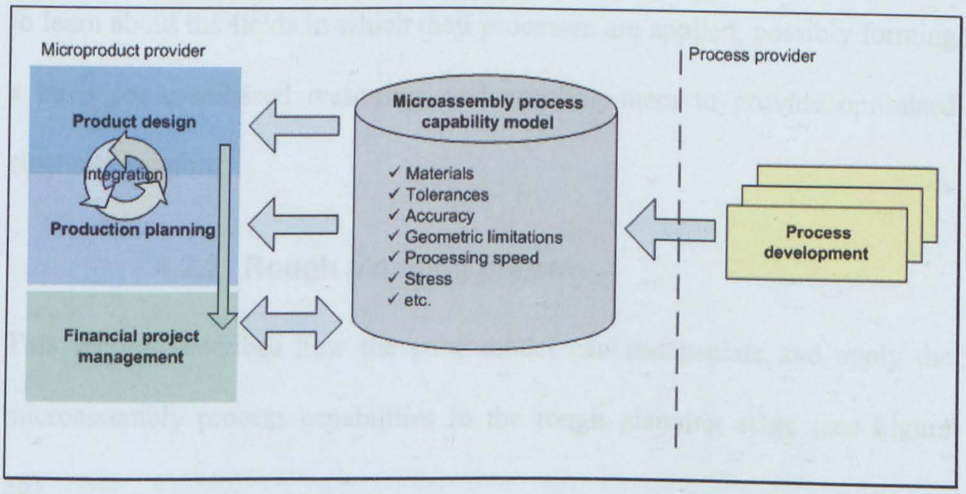

Figure 36: Organisational context of the microassembly capability model

Figure 36 demonstrates the organisational environment of the developed microassembly process capability model and its area of application. The figure distinguishes between an organisation that aims to design and fabricate a microproduct and third parties that develop assembly processes and provide corresponding equipment. With specific regard to the microproduct provider, the figure illustrates which departments will make significant use of the model. The microassembly process model offers two benefits to a *product design* department: it can be used to derive microassembly guidelines, which can be used in the product design stage, and it enables an increase in the efficiency of the design process through consideration of microassembly process characteristics. Further, the *production planning* department can utilise the assembly model to gain information on different microassembly solutions. Since the model also includes economic data, it can be used by the financial project management for cost evaluation and time analysis of the product assembly. For *OEM* the process capability model gives the opportunity to characterise their processes in a structured way and provides means to interlink product design and the production planning. This link is valuable for the OEM to learn about the fields in which their processes are applied, possibly forming a basis for case-based reasoning, and enabling them to provide optimised customer support.

4.2.2 Rough planning phase

This section describes how the cube model can encapsulate and apply the microassembly process capabilities in the rough planning stage (see Figure 35).

Generally, planning starts on the *enterprise level*, where decisions about the overall assembly facilities are made. Those decisions are reached after a considering of circumstances obtaining across the whole company: available investment funds, product development strategies, logistics, and so on. For the planning of microassembly, it is important to assess whether the existing facilities are appropriate. For example, questions have to be asked about the availability of clean room space. Another key issue to be considered here is the building's vibration insulation: traffic or construction work in nearby streets could cause unwanted vibrations that would interfere with the microassembly process. This is also important in cases where producers will be employing micromeasurement equipment to control product quality. The facility to control the environment in terms of temperature and humidity can as well be essential in the microdomain. Chapter 6 gives an overview of microassembly failures that can result from unsuitable environmental conditions (see Figure 55). More importantly, it gives guidelines on how to take environmental conditions into consideration in assembly-oriented microproduct development.

On the *assembly line level* a pre-selection of processes takes place. On the basis of the microproduct's structure it is established how many joining, feeding, and handling processes are needed. It is here that evaluations are made with regard to which microassembly processes represent possible solutions and which are ruled out.

4.2.3 Detailed planning phase

Following the *rough planning* stage, the processes have to be defined in more detail at the *workstation* level. Based on the related product and component requirements, joining processes are selected and the product design is adapted accordingly. The *process selection element* (see section 4.3) of the cube model (Figure 35) helps in identifying possible processes, from selecting from high level process classes to detailed process descriptions.

In the product design stages, the influences of the selected processes have to be continually considered. The microassembly process data (including the detailed process capabilities) are therefore represented and stored in the *process characterisation element* (see section 4.4), which forms the foundation of the cube model (Figure 35). In accordance with these data, product features can be designed, and processes and equipment modules can be defined. In the detailed planning phase, the individual product components are examined and the assembly mechanisms determined. The processes stored in the *process characterisation element* can be based on the existing pool of equipment or on data provided by OEM.

4.3 Process selection element

To gain the most benefit for the conceptual design stage, it is important to access information related to both product requirements and process capabilities. Information on the product needs to capture the envisaged product volumes, budgets on equipment and tooling, envisaged part shape types, environmental requirements, and accuracies (see section 2.2.2). In the conceptual design phase, different product solutions can already be compared. Although this does not necessarily guarantee the best solution, it considers the available conceptual product information at a stage at which it remains relatively easy to alter the product. Because of this, this procedure can be understood as cost-effective.

4.3.1 Process selection strategy

Optimum process selection is an extremely important aspect of production. Different microassembly processes have different advantages and limitations. Some processes are initially expensive (with checking or closed-loop control required) but produce high precision results requiring fewer processing steps, thus reducing the overall costs. Some are restricted to certain materials, product sizes, and shapes. The objective is to find the best match between process attributes and requirements.

Selecting the optimum process not only avoids difficulties, but directly affects the product cost and marketability (Farag, 1979). It is important to choose the right process-route at an early stage in the design before the cost-penalty attaching to making changes becomes severe (see Figure 8). That selecting of the best process is often a complicated undertaking, several processes need to be considered and may appear competitive or contradictory (Ashby, 2005).

> The selection process is no easier, and is in some regards even more complex, at the *microlevel*. As a result, it is necessary to store the microassembly capabilities in a model to facilitate optimum process selection.

Component materials, tolerances, shape, dimensions, features, feeding, handling, and joining methods, etc. need to be specified in order to choose processes appropriate to the design specifications. Because each process is characterised by different attributes, the capture of process capabilities is important for its assuring the systematic and exhaustive consideration of all available processes.

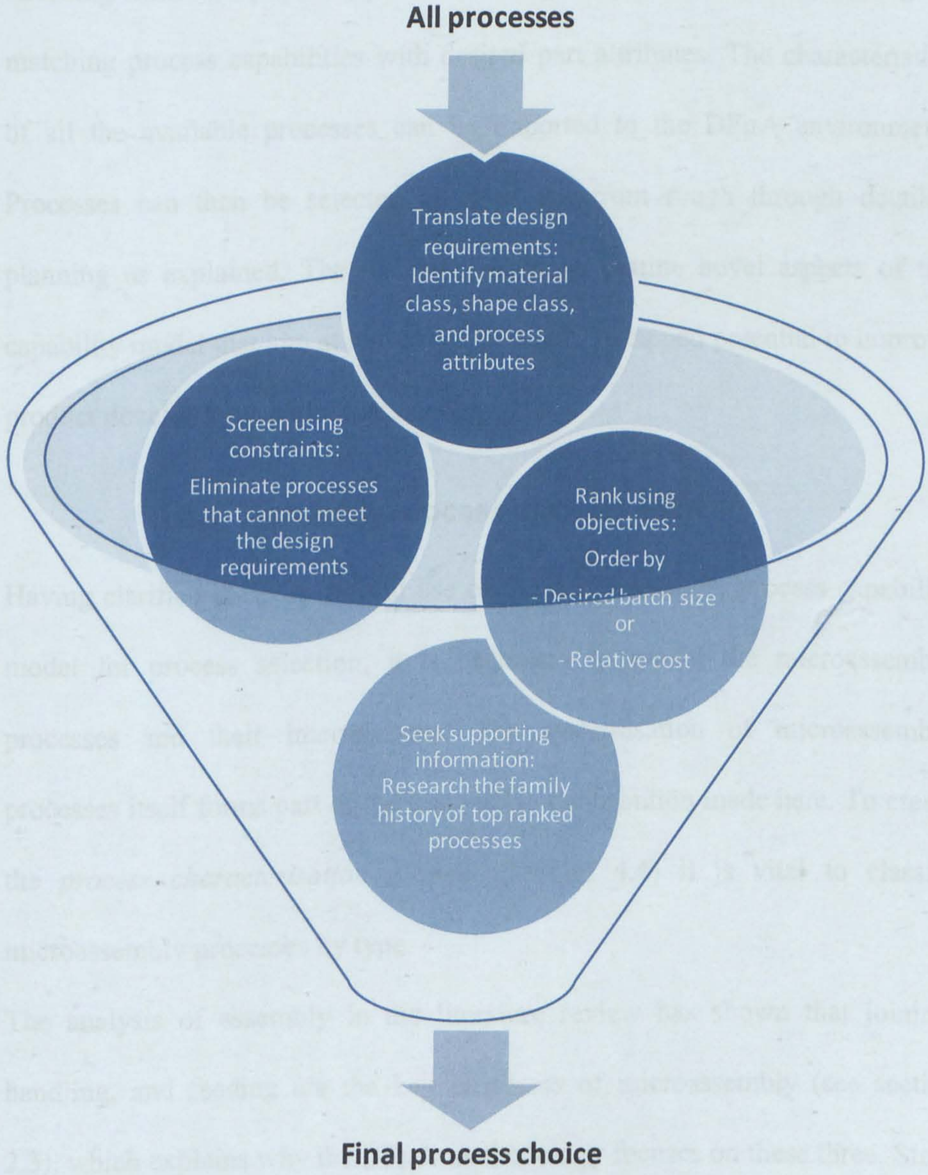

Figure 37: Process selection strategy (based on Ashby, 2005)

Process selection is an iterative procedure and the final choice has to be made by the designers and process engineers. ASHBY describes a strategy for selecting processes which can be utilised for the DFµA methodology (see Figure 37). It starts by treating all processes as possible candidates. In a step by step approach, processes are considered and eliminated until one process has been identified as providing a best fit (Ashby, 2005). Process selection means choosing from an equipment pool containing the process modules, relying on matching process capabilities with desired part attributes. The characteristics of all the available processes can be imported to the DFµA environment. Processes can then be selected or ruled out from rough through detailed planning as explained. The following sections outline novel aspects of the capability model that aim at realising a presently untapped potential to improve product development in microassembly.

4.3.2 Assembly process classification

Having clarified the purpose and use of the microassembly process capability model for process selection, it is necessary to model the microassembly processes and their interrelations. The systemisation of microassembly processes itself forms part of the knowledge contribution made here. To create the *process characterisation element* (section 4.4) it is vital to classify microassembly processes by type.

The analysis of assembly in the literature review has shown that joining, handling, and feeding are the key processes of microassembly (see section 2.3), which explains why the DFµA methodology focuses on these three. Since it serves the DFµA methodology, the microassembly capability model also takes these three processes as its focus. Under these boundary conditions,

Figure 38 shows the grouping of assembly processes used in the assembly process capability cube model. It aims at defining and interrelating terms in order to describe and characterise microassembly processes as accurately as possible. The representation of these processes, including their inputs, outputs, allocated resources, and inherent activities, is required for effective characterisation, specification, selection, and sequencing of processes. The processes need to be defined in such a way that the different capabilities of equipment can be mapped to the process domain. This is realised by a hierarchical approach, starting from a generic assembly process with relatively broad inputs and resources. The elements comprising the overall process are then categorised into joining, feeding, and handling, and their corresponding inputs, outputs, resources, and activities are listed (see Figure 38).

The three key processes are further subdivided, since it is important to understand the specific technical, temporal, and economic constraints attending each of them. The characterisation of these processes is described in detail in section 4.4. Three sets of *joining* processes have been identified for the microdomain, namely joining by adhesive bonding, through material closure (welding), and mechanical fastening. It has to be said that adhesive bonding processes are in most cases the best fit for microassembly (see section 2.3.4 on joining for the importance of gluing in the microworld).

For reasons related to the very small dimensions of the parts to be joined, mechanical fastening is generally not suitable for the microworld. However, there are a few research groups which have developed or are developing micromechanical solutions (see section 2.3.4).

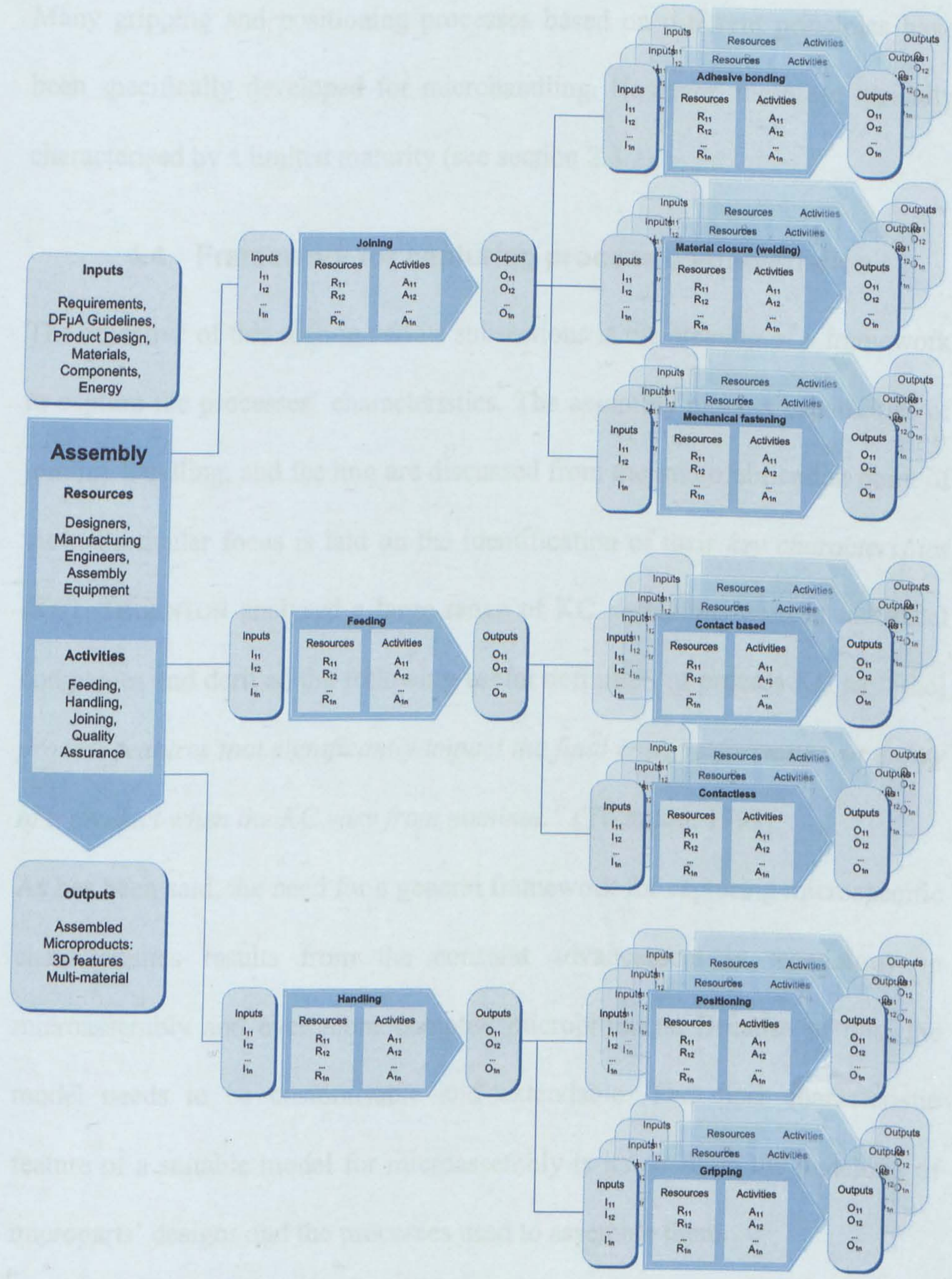

Figure 38: Grouping of assembly processes

Feeding is categorised into contact-based and contactless processes. Contactless approaches are not commonly used for conventional production; however, as has been outlined in section 2.3.3, they have real benefits for microproduction.

Gripping and positioning are the main processes in the category of *handling*.

Many gripping and positioning processes based on different principles have been specifically developed for microhandling. However, these are typically characterised by a limited maturity (see section 2.3.2).

4.4 Framework for capturing process characteristics

The objective of this section and its subsections is the creation of a framework to capture the processes' characteristics. The assembly process capabilities of joining, handling, and feeding are discussed from the microfabrication point of view. Particular focus is laid on the identification of their *key characteristics (KC)*. THORNTON analysed a large range of KC *definitions* used in industrial companies and derived the following useful definition of process KC as "[the] *process features that significantly impact the final cost, performance, or safety of a product when the KC vary from nominal.*" (Thornton, 1999).

As has been said, the need for a general framework for capturing microspecific characteristics results from the constant advancement in technology in microassembly and ever more complex microproducts. Because of this, the model needs to be customisable and extendable. The most characteristic feature of a suitable model for microassembly is its enabling the matching of microparts' designs and the processes used to assemble them.

More importantly, the integration of an assembly system can have influences on both the product design and the accuracy of the processes. It is for this reason that the tables illustrated in this section, as part of the *framework*, consider these aspects as key characteristics of the microassembly processes (captured as *'part design influences'* and *'system design influences'*).

4.4.1 Process characteristics

The fact that microassembly is an immature area with high complexity in a dynamic environment makes process characterisation a difficult task. The challenge here is to detect the KC. Hence, creating a framework for microassembly process characterisation and finding KC for its sub-processes can be seen as additional contribution to existing knowledge. The chosen characteristics have significant impact on the product and assembly system design, influencing cost and performance, and so can be recognised as the KC. For this work the KC are differentiated because an exhaustive process characterisation is too complex and time-consuming for the purpose of the model being used as part of the DFμA methodology (Chapter 5). It is sufficient instead to rely on KC. However, the framework developed does not restrict the level of detail and allows for extension of this characterisation, enabling the use of the model in other methodologies.

In the following sections, the characteristics of handling, feeding, and joining are collated and the KC are shown as analytical results.

It is important to model this characterisation in a systematic way to enable usability in both the cube model and in third party models. It has to be stressed that the aim is not to gather data for existing microassembly processes, but rather to conceptually develop the framework to enable such a data collection in a structured and usable way.

Within the DFμA approach, the process characteristics are used to support process selection and influence product design. The data are represented in process sheets (see Figure 39).

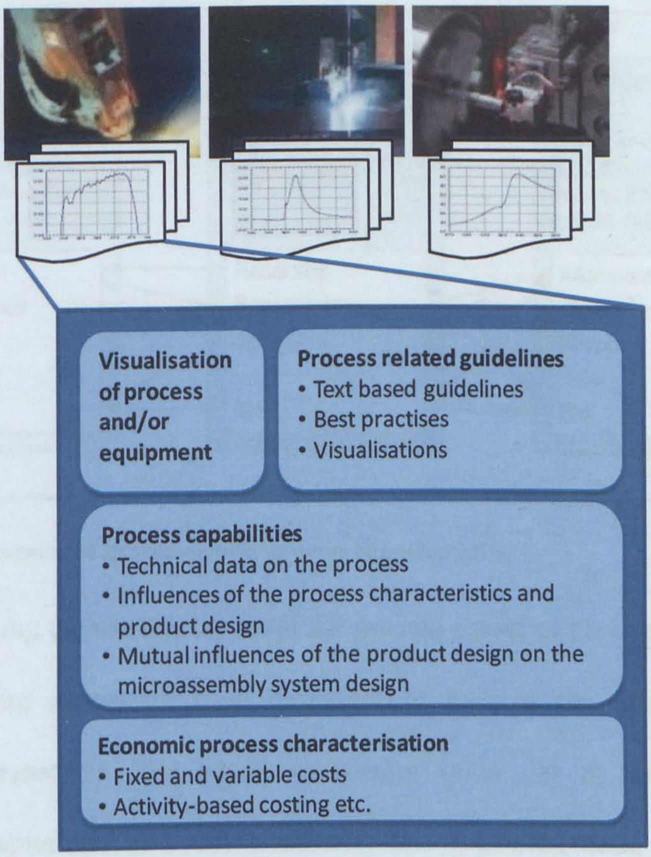

Figure 39: Schematic structure of a process sheet

The process sheets contain space for graphical representation of the actual process and/or its equipment for visualisation purposes. It contains as well technical data on the process by which microassembly process selection is conducted. Further, it offers information regarding factors which might then influence the design of the components to be processed (this information will be concerned with issues such as materials, shape, and tolerances). Economic data and important system integration aspects should also be represented.

Since the process characterisation tab provides the key element of the cube model, it is important to provide the process data in a structured way. It is for this reason that the microassembly process characteristics are captured in tables providing the required data on the process properties and on the influences these have on the product and system design (see Figure 40).

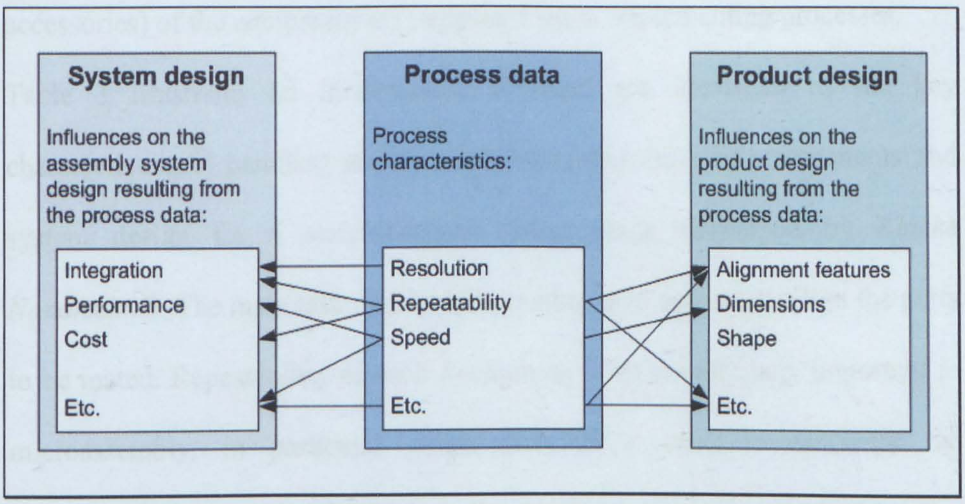

Figure 40: Influences of microassembly process characteristics

After describing the use and layout of the process sheets as they appear for the designer being supported, it is important to look at the microassembly processes themselves. The added knowledge value lies in the structured systematic capture of their characteristics. The following three subsections provide a framework for capturing characteristics of microhandling (section 4.4.2), -joining (section 4.4.3), and -feeding (section 4.4.4).

4.4.2 Capturing characteristics of handling

The state-of-the-art in handling as a critical part of microassembly has been described in section 2.3.2. In the definition provided through the grouping of assembly processes (Figure 38), handling includes micropositioning and –gripping. For the purpose of capturing their characteristics, though, they will have to be addressed separately.

Micropositioning

The key characteristics of positioning processes are related to their resolution, repeatability, workspace (stroke, reach), DOF, payload, speed, and their vacuum compatibility. Furthermore, the dimensions and modularity (control, accessories) of the equipment are important when implementing processes.

Table 3 illustrates an instantiation of what are identified as the key characteristics of handling and the influences they have on components and system design for a state-of-the-art linear stage developed by *Klocke Nanotechnik*. The main task of micropositioning is to accurately align the parts to be mated. Repeatability of such positioning units is extremely important in microassembly, in particular when there is a want to automate the microassembly process. The table is designed in such a way as to provide a means of capturing the essential data on both linear positioning units (x-, y-, z-stages) and robotics.

Table 3: Capturing characteristics of positioning processes

	Linear stage – Klocke Nanotechnik	**Part design influences**	**System design influences**
Resolution	2nm	Accuracy, self-alignment features,	Passive alignment
Repeatability	<10nm	Accuracy, self-alignment features, passive alignment	Vibration, controlled environment, materials (thermal expansion coefficients)
Workspace (stroke, reach)	20mm	Dimensions, product structure	Integration of axis
DOF	1	Product structure, layout	Integration of axis
Payload	2000g	Material, geometry (mass)	
Speed	5mm/s		Cycle time
Operational restrictions	horizontal operation, sensitive to torque		System integration
Equipment dimensions Length (stroke direction) Width (max) Height	 50mm 28mm 20mm		System dimensions, integration
Modularity (control, accessories)	Combination with other stages possible. Gripper and force sensor attachment possible.		System integration
Vacuum compatibility	yes		Needed or not (this resulting from part requirements)

If a positioning process does not provide sufficient repeatability (e.g. due to budget restrictions) it can be possible to compensate for this through changes in the system design. This might be done by using passive alignment structures or by making design changes in the microparts by integrating self-alignment features into them (see sections 6.3.2 and 6.3.3 on DFμA guidelines with regard to self- and passive alignment). If high repeatability is desired, it is important to design the system environment in a way that allows for the full realisation of the potential capability of the positioning process (e.g. integration of linear stages). Where this is to be done, it is necessary to ensure that the positioning units are entirely undisturbed by local sources of vibration e.g. other processes or even activity on a nearby street. Uncontrolled heat flow, e.g. from light sources, can also compromise the desired accuracies. For this reason as well it can be necessary to exercise a high degree of control over the assembly environment.

Miniaturisation requires not only that the components become smaller but demands the same as well of the process equipment, a fact clearly illustrated by the growing trend towards desktop factories. Accordingly, the sizes of the positioning units are also captured in the table.

Microgripping

Gripping represents one of the most characteristic processes in microassembly, needed to pick objects up and place them in a different position. This pick-up and placement of microparts is beset by a range of difficulties (see section 2.4.1). The framework for capturing the microgripping process characteristics is outlined as follows. Following that framework, data on the characteristics of gripping equipment and their influences on the product and system design have to be supplied by the OEM.

The kind of gripping mechanism to be employed has a particularly strong influence on component design or is determined by it. An example illustrating the relationship between the part design and the gripping mechanism is the need for a relatively flat surface when using a vacuum gripper. In addition, a vacuum gripper poses restrictions on the material to be used, e.g. surfaces are unsuitable if too flexible or too porous. The main way in which the gripping process to be used can influence the design of the part is that it might delimit choice with regard to the fragility of the part, component dimensions and shape (e.g. alignment features such as gripping slots, surfaces etc.), and type of material to be used.

Choosing a microgripping process depends on the properties of the part to be handled considering its material, dimension, shape, fragility, surface finish and sensitivity (contamination through contact). The process provider should also provide guidelines on how components can be designed to optimise the gripping process. The key characteristics of gripping processes are related to their stroke (opening and closing of the gripper), gripping force, provision of force feedback, payload, sizes of graspable object, equipment dimensions, modularity of tips, and vacuum compatibility (see Appendix F for an instantiation of gripping).

In microassembly it is problematic when objects are not in the exact position or defined orientation. This problem can be solved by expensive object recognition systems or intelligent gripper and part design. Sticking effects in particular serve to make gripping in the microdomain difficult (see section 2.4.1 for more details). A summary of guidelines on how to reduce these sticking effects is provided in section 6.3.4, while section 6.3.5 focuses on guidelines that aim at optimising micropart gripping.

4.4.3 Key characteristics of joining

Joining two previously separate workpieces into a newly formed part is a difficult process within microassembly, due to the small scale of the parts (joints require space). The ideal solution would be to avoid assembly and joining in general (*zero-assembly approaches*). However, this is not possible yet. Joining is particularly necessary when parts are being assembled from different materials and when complex three-dimensional structures have to be created. The critical joining characteristics depend on the joining mechanism and are related to the realisable joint size (joining area to be occupied), the joining strength, the speed of the joining process (cycle time), the introduction of tension and stress through the joining medium or process, the operating temperature, the joinable materials, and the durability/lifetime of the joint. The process provider should supply guidelines on how the product and assembly system components can be designed to optimise the joining process. In that context it is essential to capture to what extent functions can be integrated in the actual joint or joining medium, what restriction are imposed by the size and modularity of the actual equipment, and whether the process is vacuum compatible or not.

A particularly important aspect of joining in the context of microproduct design is the possible integration of functions into the joint itself. For example, the joint can be designed to insulate, or to conduct light, heat, electricity etc. (see section 6.3.6). The main impacts on the part design resulting from the joining process are related to the material and the part dimensions and shape. In particular the parts' surface properties, such as surface finish or -sensitivity (e.g. to possible contamination through the joining medium), need to be designed according to the joining process selected.

In that context it has to be stated that adhesive bonding technology is characterised by a range of advantages for microassembly (see section 2.3.4). It allows the joining of dissimilar materials. Low heat joining of this type is advantageous because it induces little or no mechanical stress (in addition, the stress is evenly distributed). In fact, adhesive joining offers a range of possibilities for integration of functions into the joint and thereby into the product. Section 6.3.6 summarises microproduct design guidelines related to joining with glue. Due to the importance of adhesive joining in microassembly, additional tables have been developed to capture the characteristics of the adhesive dispenser and the adhesive medium (Table 4 and Table 5).

Table 4: Adhesive dispensing

Dispensing mechanism	
Dispensing volume	µl
Dispensing area	μm^2
Time control	s
Dimensions	µm
Modularity (integration to stages or robotics,)	
Vacuum compatible	Yes/no

Table 5: Adhesive material

Curing mechanism	UV light, air
Curing time	s
Joining strength (dependent on joint area)	N
Tension	N
Conduction of heat	W/(m·K)
Conduction of light	Yes/no
Conduction of electricity	Yes/no
Viscosity	Pa·s

4.4.4 Key characteristics of feeding

Micropart feeders need to present components to an assembly station at the same position, in correct orientation, and at the right speed. Particularly in microassembly it is necessary that the feeding mechanism provides a precise pick up position while avoiding damage or contamination of sensitive part surfaces (section 2.3.3). Depending on the feeding mechanisms the key characteristics of the feeding process are related to the feeding rate (parts/minute) and accuracy of the part orientation that can be realised. Furthermore it is important to capture the payload, flexibility, and size of components to be fed because they characterise the feeding process.

As well as surface sensitivity (e.g. functional surface), component dimension, shape, and mass are important factors to consider when relating the product design to a suitable feeding technology. Feeding presents a link between the macro- and microworlds. That is to say, the loading of magazines, for example, needs to be enabled. It is important to identify potential disturbances (e.g. heat or vibration) caused by a feeding mechanism and decouple the positioning and joining processes from the feeding mechanism where necessary.

The development of the microassembly process capability model can be understood as fundamental in opening up further research areas for the microdomain, e.g. *automatic reasoning* in the design and process selection. In the process of validating the developments presented here through two practical test cases (see chapter 7) several *instantiations* of the framework have been realised. Appendices E and F provide an overview of these.

This chapter having described the developed process capability model (see cube model, section 4.2) and defined and outlined its essential constituents, namely the process selection- and the process characterisation element, the next chapter introduces the overall DFμA methodology, showing how the model is utilised.

5 DFμA methodology

This chapter describes the development of the overarching DFμA structure, which connects and bridges different design phases, and provides a flexible framework for microassembly-oriented product design. The methodology describes and defines the overall organisation to translate the microassembly capability model into practical application.

The chapter is structured as follows: first the significance of the DFμA methodology is explained (section 5.1). That is, its contribution to product design in the microworld is made clear. The implications resulting from existing microdomain challenges are elaborated on, and then there is an explanation of how the limitations of current DFA methods can be overcome.

Following these analyses, the conceptual development of the DFμA methodology is described (section 5.2). Generally applicable properties which need to be included in the development of design methodologies are outlined. The scope of the DFμA methodology is narrowed and the stakeholders involved are identified and characterised. The main functions of the methodology are defined on the basis of *use cases* for the DFμA environment. The layout of the methodology and integration of its underlying models are described. In section 5.3, the key phases of the methodology are explained, reaching from conceptual product design over product analysis to analysis of process routes.

5.1 Significance of the overall DFμA methodology

"Design methodology [...] is a concrete course of action for the design of technical systems that derives its knowledge from design science [...] and

from practical experience in different domains. It includes plans of action that link working steps and design phases according to content and organisation" (Pahl *et al.*, 2007).

With respect to the given definition, this chapter aims at outlining a *"concrete course of action"*, i.e. the overall DFµA methodology. Figure 41 applies the definition of design methodology quoted above to the developments carried out in this research.

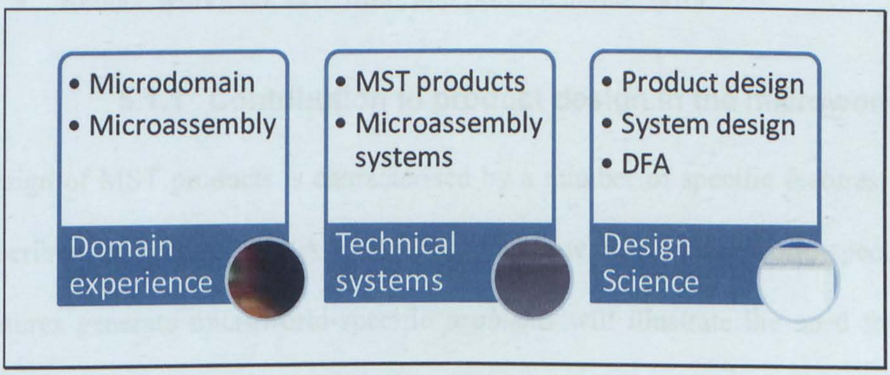

Figure 41: Scope of design methodology

The *"technical systems"* are represented by the microproducts and microassembly systems which have to be designed. The knowledge required comes from *"practical experience,"* (i.e. of microdomain-specific characteristics and from information gathered about microassembly-specific processes). It is captured in and provided through the microassembly capability model (see Chapter 4), clarifying the importance of adapting both the design of microparts and their microassembly processes. This is done by providing the designer with knowledge about the process domain in the design stage. This knowledge has to be provided in a structured way based on existing *"design science."*

The layout design of the DFµA methodology is important because it is key to enabling the structured approach described above. According to PAHL *ET AL.* design methodology built on existing design science should (Pahl et al., 2007):

- Support the search for ideal solutions
- Not rely on finding solutions by chance
- Facilitate the transfer of proven solutions to related tasks
- Be suitable for electronic data processing
- Lend itself to being taught and studied
- Reduce workload, save time, and prevent human error

5.1.1 Contribution to product design in the microworld

Design of MST products is characterised by a number of specific features, as described in section 2.2. A considering of how these microworld-specific features generate microworld-specific *problems* will illustrate the need for a bespoke methodology, one tailored specifically for the microworld. The need to provide such a structured and domain-specific approach informs the developing of the procedural DFμA methodology. Described below are specific issues it is intended to address:

- Designing in the microworld is highly knowledge intensive, resulting in the need for often *costly and time consuming consultation.* This is in part an unavoidable product of the dynamic and complex nature of the field, but it is in large part as well a consequence of the *lack of standardisation.*
- To a greater extent than is true in conventional assembly, the microassembly task to be performed depends on the components and their arrangement in the product. MST products are characterised by a very high degree of integration of both functions and components. And,

MST product design is driven by advances made in what is a very fast moving field.

The issues described above make it clear that research dealing with product design in the microworld cannot be carried out without consideration of microassembly technologies, processes, and their characterisation (see section 4.4). DFA methods and microassembly processes need to be brought together in a holistic approach to support the transfer of research prototypes to successful microproducts.

The lack of decision support means that current solutions for microproduct assembly are often far from optimal (see Figure 42).

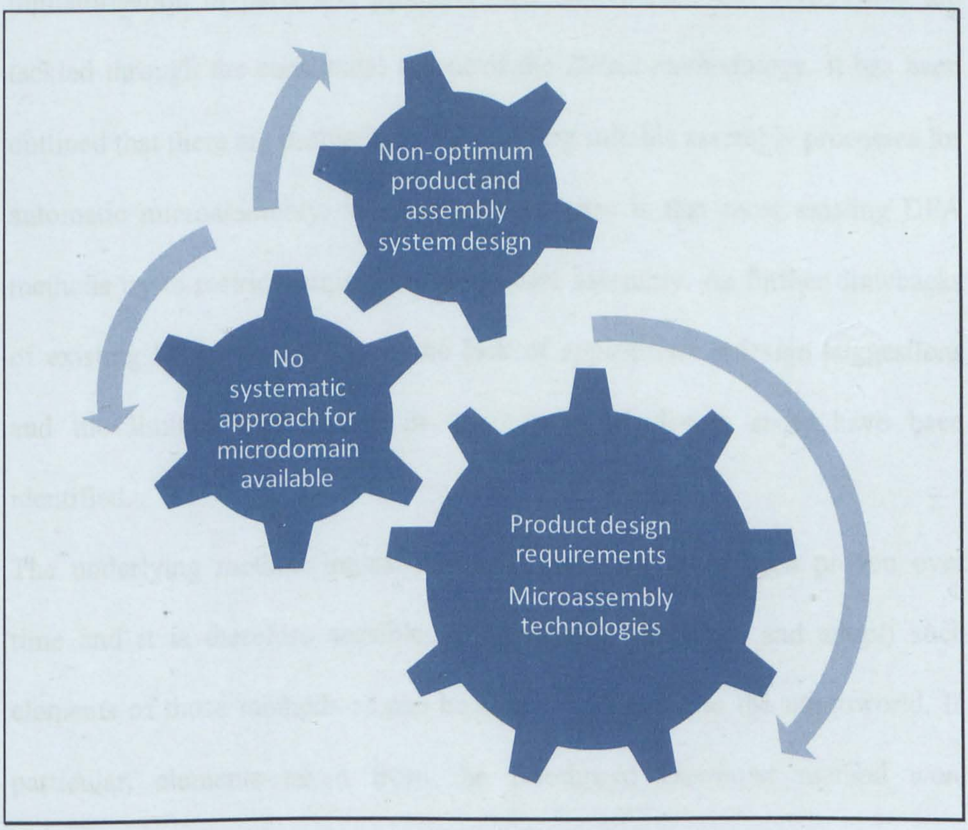

Figure 42: The microdomain needs a structured approach to product and system design

5.1.2 Addressing the limitations of current DFA methods

The work presented in this PhD thesis aims at assisting the designer by incorporating microassembly-specific knowledge in the process of designing microproducts. From early stages in the design onwards, the designer is to be supported in a systematic way in developing microproducts, assuring their parts can be fed, handled, and joined. Because current methods are often not satisfactorily applicable to the world of microassembly (see section 3.1), the development of the *DFμA methodology layout* is essential..

The literature review has shown that new challenges arise due to increasing miniaturisation of parts and products (see sections 2.2 and 2.4). These are tackled through the conceptual layout of the *DFμA methodology*. It has been outlined that there are problems in determining suitable assembly processes for automatic microassembly. What is also the case is that most existing DFA methods try to restrict miniaturisation to ease assembly. As further drawbacks of existing DFA methodologies the lack of appropriate redesign suggestions and the limited applicability in the conceptual design stage have been identified.

The underlying methodological concepts, however, have been proven over time and it is therefore sensible to incorporate (or adapt and adopt) such elements of those methods as can be shown applicable to the microworld. In particular, elements taken from the Boothroyd Dewhurst method were examined for the development of the DFμA methodology structure.

5.2 Development of the DFµA methodology

5.2.1 Required properties of the DFµA methodology

DFA methodologies have been employed in conventional assembly for approximately thirty years, and numerous different DFA methodologies have been developed over that time (see Figure 21). This history has provided a broad template that can be understood as common to all good methodological approaches. The features of that template are necessarily general and are only related to the design of *the methodology*. It is for this reason that they can be transferred to the microdomain. Design for assembly methods should be: (Redford and Chal, 1994):

- *Complete*: The method should focus on both objectivity (e.g.. evaluation of assembleability) and creativity (e.g. procedures for improving assembleability).
- *Systematic*: The method should follow a step-by-step approach to assure that all important aspects are considered.
- *Designed to allow for Measurability*: Traditionally, the objective, accurate, and complete measurement of assembleability is one of the central problems of DFA. The aim of assembleability evaluation is to find the optimal combination of influence factors.
- *User-friendly*: *"The user-friendliness of any DFA methodology is critically important as it determines implementation cost and designer effort"* (Redford and Chal, 1994). The tool should not require excessive introductory training courses (Eskilaender and Byron-Carlsson, 1998 cited in: , Eskilaender, 2001).

ESKILAENDER AND BYRON-CARLSSON'S study produced the following requirements that any DFA-tool should fulfil in order to be easily applicable (Eskilaender and Byron-Carlsson, 1998, cited in: Eskilaender, 2001):

- *Support of cross-functional teams*: The DFA tool should capture aspects that require knowledge and expertise from various disciplines, e.g. manufacturing engineers, quality engineers, and cost engineers.
- *Transfer of knowledge*: Gained experiences and knowledge from accomplished projects should be recorded, so they can be transferred to future projects to avoid repetition of mistakes.
- *Cost analysis*: The possibility to compare two different product solutions supports the decision-making.
- *Geometric product evaluation*: If there is a high level of geometric complexity in the required assembly processes, the assembly system is likely to be expensive and unreliable. A DFA method should indicate the complexity of a product from an assembly point of view and try to make it simpler in order to lessen the cost of the assembly system.
- *Software*: The methodology should be easy to implement in a software tool, so as to assure ease of use.

The conceptual structure of the DFμA methodology, considering most of the requirements described, is presented in the following sections.

5.2.2 Involved stakeholders and main functions

The generic requirements having been outlined, this section focuses on more specific functional demands for the DFμA methodology resulting from the involvement of different stakeholders. The Unified Modeling Language™ (UML) has been applied to capture and display these requirements. UML is a standardised universal modelling language developed by the Object Management Group (OMG). It supports the specification, visualisation, and documentation of software system models, including their structure and design. The OMG suggests *use case diagrams for gathering of requirements* (OMG, 2005).

Figure 43 shows the UML use case diagram that was created for the development of the DFµA methodology. It shows the relevant stakeholders involved with the methodology, namely:

- *Client*
- *Product designer*
- *Equipment provider*
- *Manufacturing engineer (system integrator)*

The use case diagram displays three subsystems (system boundaries) in which the use cases and their interactions with the actors are placed:

- *Requirements specification and conceptual design*
- *Design for microassembly environment*, representing the main functions of the DFµA methodology
- *Production planning and control*

These subsystems represent relevant stages in the product development process (see section 2.2). Anything within a box (system boundary) represents functionality that is in scope of that relevant stage.

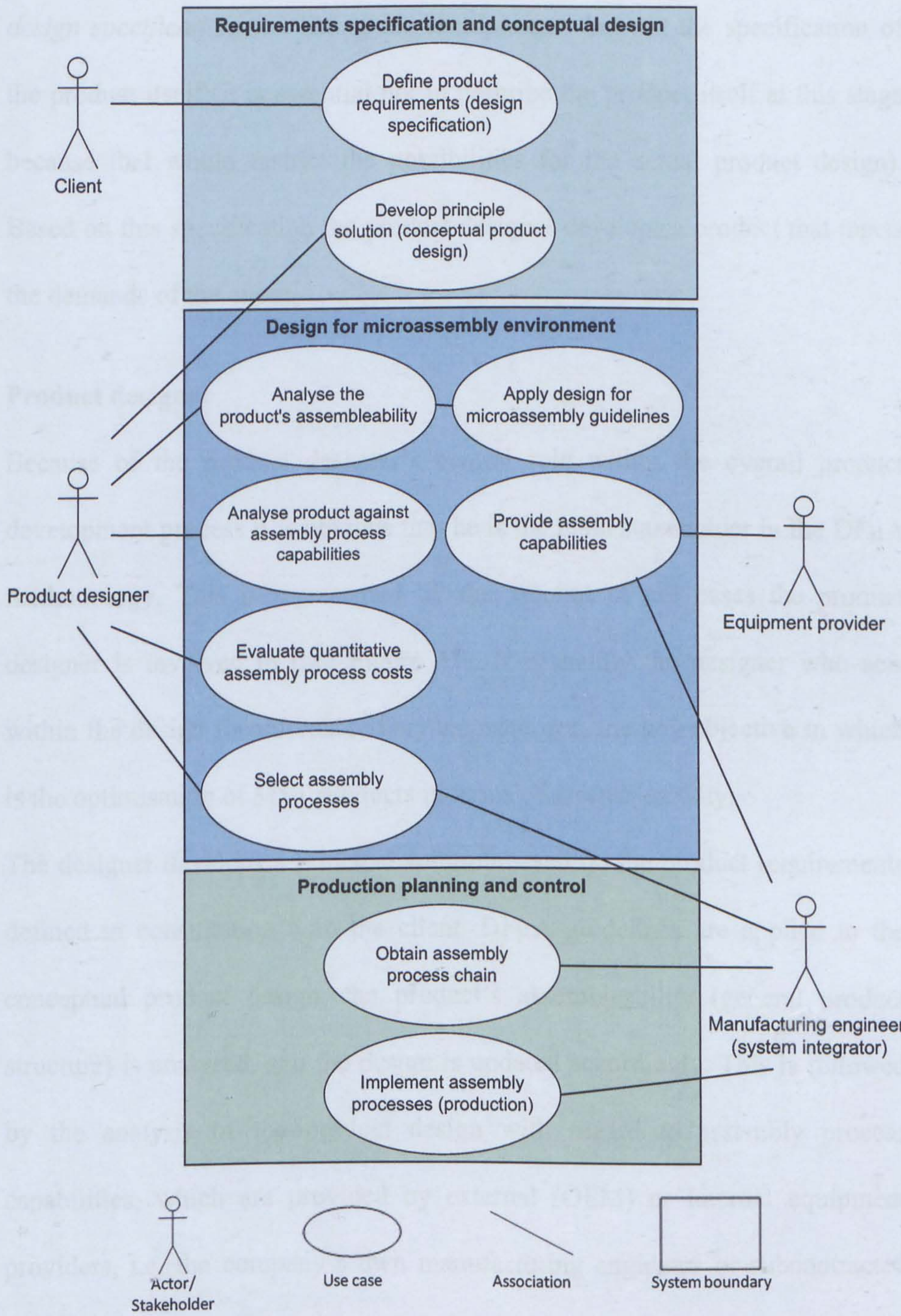

Figure 43: DFµA methodology development - UML use case diagram

Client

The client can be either company-internal (a department that requires a solution to a specific problem) or -external, for instance a customer who needs a certain kind of functional product. The client typically provides the *product* *design specification*, i.e. listing the requirements but not the specification of the product itself (it is essential not to describe the product itself at this stage because that would restrict the possibilities for the actual product design). Based on this specification the product designer develops a product that meets the demands of the client.

Product designer

Because of the product designer's central role within the overall product development process it is obvious that he is the main stakeholder in the DFμA methodology. This is represented by the amount of use cases the product designer is involved in (see Figure 43). It is mainly the designer who acts within the design for microassembly environment, the key objective in which is the optimisation of MST products in terms of assembleability.

The designer develops a principal solution based on the product requirements defined in consultation with the client. DFμA guidelines are applied to the conceptual product design, the product's assembleability (general product structure) is analysed, and the design is updated accordingly. This is followed by the analysis of the product design with regard to assembly process capabilities, which are provided by external (OEM) or internal equipment providers, i.e. the company's own manufacturing engineers or subcontracted system integrators. The process data made available (including indications on fixed and variable costs) enables the design team to directly compare the cost of different assembly processes. Design adaptations related to the candidate microassembly processes can be considered before involving the manufacturing engineers or engaging with an external system integrator to plan and implement the actual assembly system (production planning and control).

Equipment provider

The equipment provider is an external entity that develops assembly processes and provides corresponding equipment. This actor possesses microassembly process knowledge and provides information about the assembly capabilities of the equipment, such as relevant data on accuracy, repeatability, speed, cost, applicability (materials, environment etc.), and so on. The product designer can then analyse his product design with regard to these capabilities. The process capability model introduced in Chapter 4 gives the equipment provider a means of characterising the processes in a structured way.

Manufacturing engineer (system integrator)

The manufacturing engineers provide assembly process capabilities for company owned assembly equipment and customised developments for which data is not publicly available. In addition, being experts in the manufacturing domain, they consult with the product designer in deciding the microassembly processes. This coordinated effort links to the *production planning and control* phase which works with the outputs of the DFμA environment. The manufacturing engineer (or system integrator) determines the assembly process chain in detail and implements the assembly processes.

Financial controller/advisor

The financial advisor is not shown in Figure 43 because he does not directly interact with the DFμA environment. Nevertheless, he can get involved by supplying economic data (e.g. via activity-based costing approaches) about assembly processes that exist within a company already, i.e. providing economic assembly capabilities. The financial controller can be involved in the cost evaluation of possible assembly equipment (e.g. providing existing data, calculation of investment cost/amortisation, target costing etc.).

Use cases - DFμA environment

The definition of *use cases* in this section was used to identify, clarify, and organise the DFμA environment system requirements, namely:

- Analyse the product's assembleability
- Apply DFμA guidelines to optimise the design solutions (including the conceptual product design)
- Provide assembly capabilities
- Analyse product design against assembly process capabilities
- Evaluate qualitative assembly process costs
- Select assembly processes

The use case diagram (Figure 43) shows the relevant stakeholders and contains all system activities that have significance to these users. Possible sequences of interactions between the stakeholders and the DFμA environment, aiming at an optimised design of microproducts, are highlighted. The *basic course of action* from a client's request (triggering event) through the DFμA environment's objective of optimised microproduct design to an implemented assembly system is shown. A tabulated overview of all use cases is provided in Appendix A.

5.2.3 DFμA methodology structure

Building on the identification and description of the system requirements for the DFμA environment by applying the *UML use case methodology* in the previous section, this one defines the conceptual layout of the DFμA methodology. The work presented here aims at outlining the development of the DFµA methodology structure, making use of the developed microassembly capability model. The target of the layout is to assist the designer by incorporating microassembly-specific knowledge so as to generate microworld-specific guidelines.

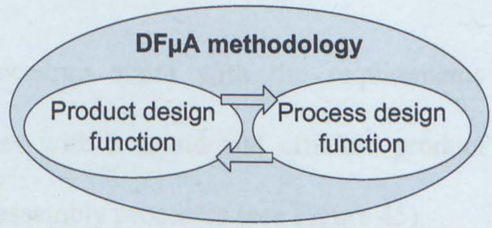

Figure 44: Core functions of DFµA

The tried and true Boothroyd Dewhurst DFA method was not developed with the microworld in mind. In addition, it has been suggested already that the Boothroyd Dewhurst method is characterised by shortcomings in the early conceptual product design stages, e.g. the information needed in order to use the method is not available in the *conceptual* product design stage.

Nevertheless, basic methodological elements of Boothroyd Dewhurst's concept can still be valid in the microworld (see section 3.1). They are utilised for the development of the procedural structure of the DFµA methodology shown in this section. Therefore, the objectives guiding the development of the structure can be formulated as:

- To *facilitate design improvements* early in the design process by applying design rules and guidelines which are focused on the microworld to cope with its specific challenges.
- To consider key assembly process features in early design stages.
- To determine the appropriate microassembly processes by considering process-related requirements.

In the previous section the functional requirements of the DFµA environment have been defined with the help of use cases (see Figure 43). In addition, the objectives listed above make clear that it is essential to marry two functions in the DFμA methodology: a product design function and a process design function (see Figure 44).

In principle the methodological procedure starts with the requirements provided by the customer and finishes with a sound and efficient product design and a chain of applicable microassembly processes (see Figure 45).

The first design specifications will be based on those product requirements which have greatest influence on the design, mainly functional requirements. Although only conceptual drawings are needed, more comprehensive information leads to a more effective result. That initial product design will be analysed in terms of assembleability and complexity (*use case: analyse the product's assembleability*) and evaluated by applying the DFμA guidelines[10] to the conceptual product design (*use case: apply DFμA guidelines to optimise the design solutions*). After updating the product design based on the input/feedback from the DFμA guidelines and the product analysis, the next step is the *process-product analysis* which is the key to the methodology (*use case: analyse product against microassembly process capabilities*).

[10] The results of the DFμA guideline analysis are described in section 6.2.

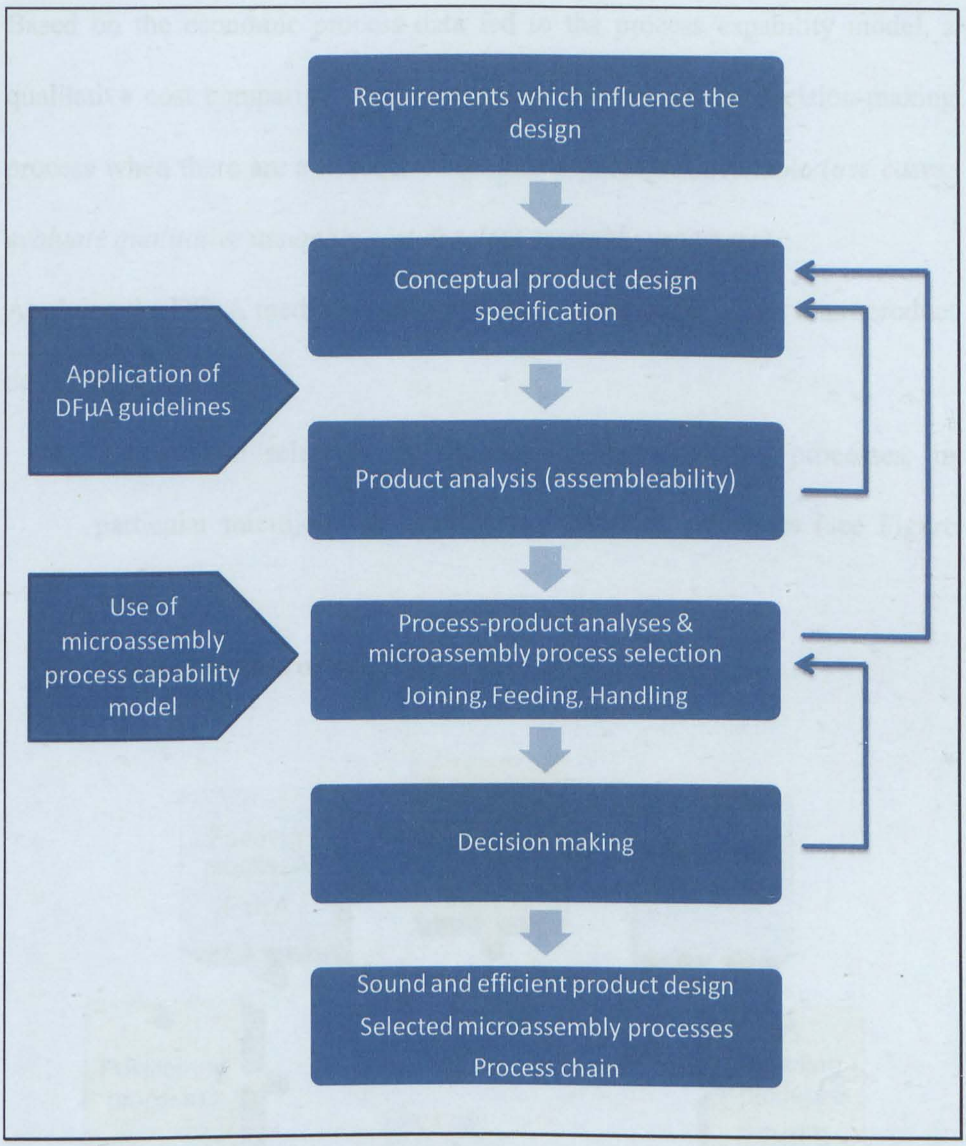

Figure 45: Layout of the DFμA methodology

It is because each process is characterised by different attributes that the use of a process capability model in the DFμA methodology is of such importance. The aim is to provide at an early stage in the *product design process* information regarding such factors related to the *assembly process* as might helpfully be considered in deciding on the product's (or products') design. The situation is two-way as information regarding the anticipated relationship between product and process can be used to determine the assembly processes to be employed.

Based on the economic process data fed to the process capability model, a qualitative cost comparison can be accessed to support the decision-making process when there are a number of candidate processes available (*use cases: evaluate qualitative assembly cost & select assembly processes*).

Applying the DFμA methodology results in a sound and efficient microproduct design leading to:

- A complete selection of appropriate microassembly processes, in particular microjoining, feeding, and handling processes (see Figure 46).
- A determination of the chain of assembly processes.

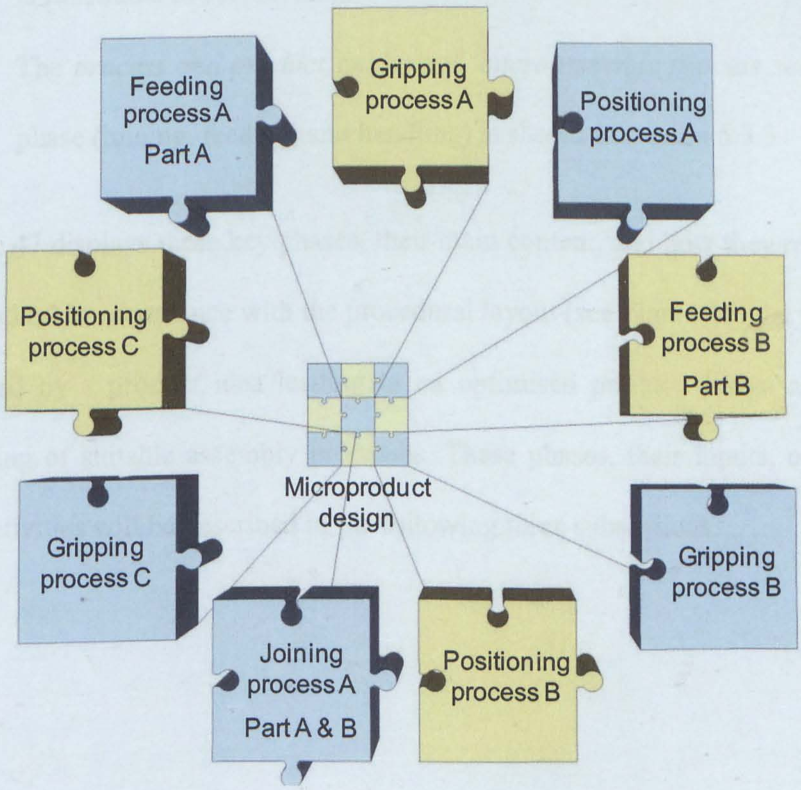

Figure 46: Process selection outcome

5.3 Key Phases of the DFμA methodology

Section 5.2 having outlined the development of the DFμA methodology in discussing the required properties, analysing its application to use cases, and defining the procedural layout, this section explains its key phases in more detail (see Figure 45):

- The *conceptual product design specification* phase, representing the early phase in developing the microproduct, is described in section 5.3.1
- The *product analysis* phase, applying basic rules to optimise the microproduct design in terms of complexitiy and thus assembleability, is illustrated in section 5.3.2
- The *process and product analysis & microassembly process selection* phase (joining, feeding, and handling) is shown in section 5.3.3

Figure 47 displays these key phases, their main content, and how they relate to each other. In accordance with the procedural layout (see Figure 45) the flow is initiated by a product idea leading to an optimised product design and the selecting of suitable assembly processes. These phases, their inputs, outputs, and activities will be described in the following three subsections.

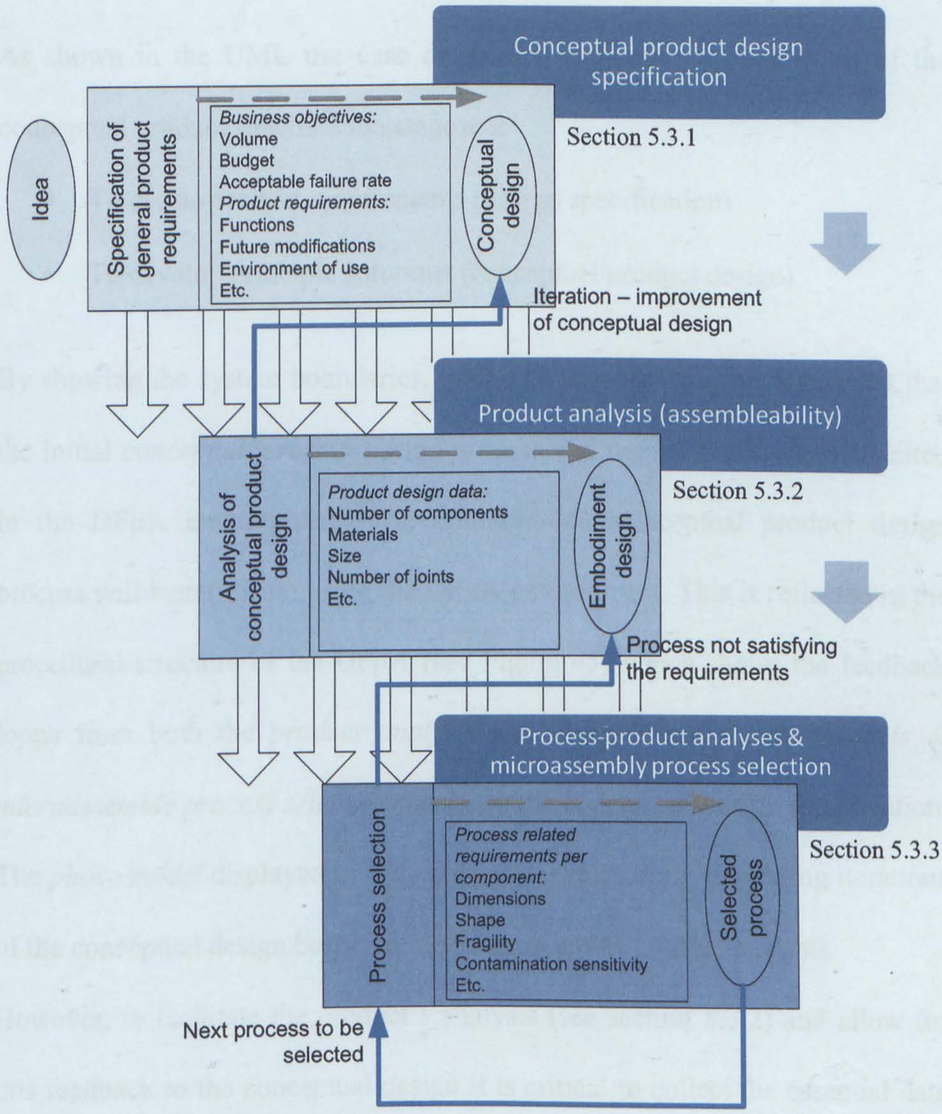

Figure 47: Phase model as part of the DFµA methodology

5.3.1 Conceptual product design specification

"Conceptual design is the part of the design process where – by identifying the essential problems through abstraction, establishing function structures, searching for appropriate working principles and combining these into a working structure – the basic solution path is laid down through the elaboration of a solution principle" (Pahl *et al.*, 2007).

As shown in the UML use case diagram (see Figure 43), the goals of the conceptual product specification stage are:

- To define product requirements (design specification)
- To develop principle solutions (conceptual product design)

By showing the system boundaries, the UML use case diagram illustrates that the initial *conceptual product design process* will not be directly implemented in the DFμA environment.[11] Nevertheless, the conceptual product design process will benefit from using the DFμA environment. This is reflected in the procedural structure of the DFμA (see Figure 45) which shows the feedback loops from both the *product analysis* and the *process-product analysis & microassembly process selection* phases to the conceptual design specification. The *phase model* displayed in Figure 47 also shows these improving iterations of the conceptual design based on feedback from the product analysis.

However, to facilitate the product's analysis (see section 5.3.2) and allow for this feedback to the conceptual design it is critical to collect the essential data and feed it into the DFμA environment.

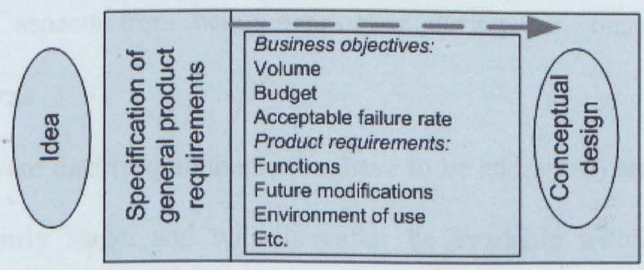

Figure 48: Conceptual product design specification – as part of the phase model

Figure 48 (extract of the *phase model*, see Figure 47) illustrates the flow within

[11] However, general DFμA guidelines will be available for the designer's consideration in the conceptual design stage. These guidelines and their applications are dealt with in chapter 6.

the *conceptual product design specification* phase. General product requirements are defined by the customers based on their product ideas. These requirements form the basis for developing a solution that can realise this idea. In fact, they can be seen as a methodological step within the development of a suitable solution. The outcome of this phase is a conceptually designed product. The requirements-list typically contains the demands and wishes of the customer. Demands have to be realised within the design because otherwise the customer would not accept the proposed product. Requirements form a supporting framework throughout the design process, where the demands stay the same and the wishes might be subject to changes. Clearly this supporting framework needs to be captured for the DFμA environment as early as possible. To do this the environment will ask for data such as envisaged production volume, budget on equipment and tooling, acceptable failure rates, specifics in the environment of application etc. (see Figure 48). This information gathering and the facility to provide it in a systemised fashion serves two purposes:

- The designer is guided to a certain extent by the system's preventing vital aspects from being overlooked during the conceptual design process
- Relevant data (requirements that have to be addressed) are collected at an early stage, and will thereafter be available within the DFμA environment throughout all subsequent phases in the process, assuring user-friendliness (see section 5.2.1)

The following subsection will deal with the product analyses, describing how the conceptual product design is carried out, and how it is further developed to the embodiment design.

5.3.2 Product analysis

Once the general product requirements are captured and an initial product design is available, it will be analysed by evaluating the parts' complexities and considering of DFμA guidelines. On that basis the product will be further developed until a complete embodiment design is available (see Figure 49, extract from Figure 47). Alongside this flow of development, ever more characteristics of the product and its parts become available. These product design data are captured within the DFμA environment and are necessary to enable the product-process analysis with the help of the microassembly process capability model (see Chapter 4).

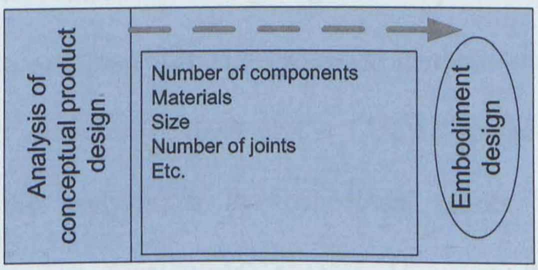

Figure 49: Product analysis

In accordance with the flow of activities outlined above, the main objectives of the product analysis are as follows:

- To analyse the product's assembleability
- To apply DFμA guidelines to optimise the design solutions (including the conceptual product design (see Chapter 6)

The designer should familiarise himself with the appropriate guidelines and assess his conceptual design against them. DFμA guidelines are derived, developed, and described in Chapter 6, and an outline of how they can be applied is provided as well.

Analysis of conceptual product design

The analysis of the conceptual design deals mainly with the assembleability of the microproduct. A problematic aspect of dealing with a conceptual design is that some product characteristics cannot be quantified directly to allow assessment of different alternatives. Furthermore, some of the product properties are not defined this early in the design stage (e.g. exact dimensions, tolerances etc.).

For these reasons, an alternative approach is proposed. That approach turns a list of *'soft'* factors into quantitative figures. These scores allow the designer to compare different designs and thus they help to highlight possible problems related to the microdomain at an early stage. The approach can be understood as similar to other well established score-based methods such as the *Failure mode and effects analysis* (FMEA) or the LUCAS method. Similar to the *Design-FMEA*, the analysis of the conceptual product design aims at optimising the product development process. However, the *Design-FMEA* typically relies on the existence of an embodiment design. Furthermore the aim of the DFμA's conceptual product design analysis is not the identifying and evaluating of all possible mistakes related to the design but the highlighting of the microdomain-specific difficulties associated with the conceptual product design. So, the DFμA is not trying to replace a possible Design-FMEA.

Within the DFμA, the analysis of the conceptual product design takes place in two steps. First, the overall product is evaluated in terms of number of components, kind and number of different materials, and number of needed joints. Second, all components are assessed with regard to their complexity based on indications on their dimensions (if available), fragility, three-dimensional structure, and so on. A number of questions will be asked based on the industry- and company-specific defined criteria catalogue *i.e. the criteria are customisable.*[12]

Each part will be given a complexity figure between **C1** and **C6** based on the designer's assessment (see Figure 50). The evaluation helps the design team to assess its design in a more objective way, stimulating discussions and increasing the chances of discovering design flaws.

A full description of C1 to C6 has been developed and can be found in Appendix B. As stated above, that criteria catalogue has to be customised according to industry- and company-specific needs. Therefore, the descriptions provided should be seen as one of several possible instantiations.

The value **C1 represents low complexity** and means that a part is characterised by the following:

- No flexibility
- No fragility (not sensitive to the exertion of any forces)
- No contact-sensitive surfaces
- Simple shapes (cube=6 surfaces)
- Joining, handling, or feeding features available for the part
- Defined surface or points available that can serve as references for the microassembly process

[12] For instance, the bio-medical industry is characterised by very specific product requirements (e.g. biocompatibility of materials for implants). In addition, the medical industry has to comply with specific regulations such as *good manufacturing practices* (GMP) imposed by bodies such as the *US Food and Drug Administration* (FDA).

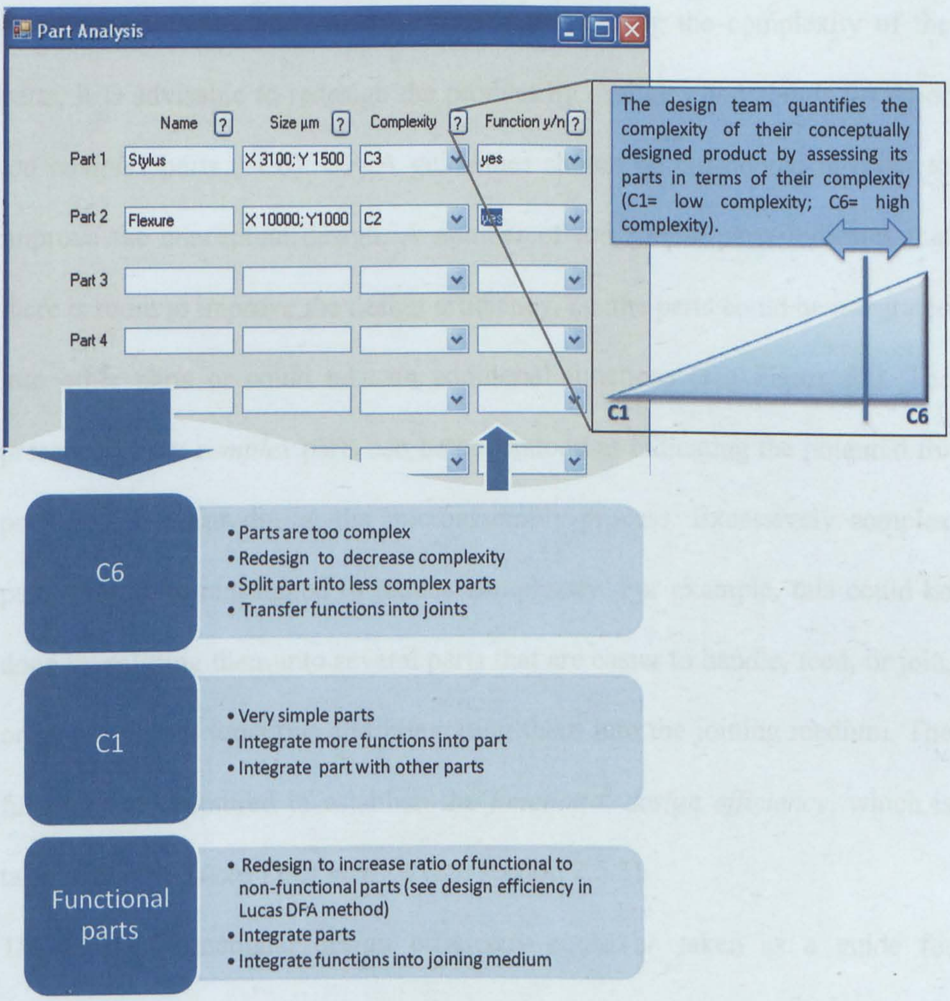

Figure 50: Complexity analysis of conceptual design

The value **C6 represents high complexity** and means that a part is characterised by the following:

- High degree of flexibility
- High degree of fragility (sensitive to the exertion of any forces)
- All surfaces are sensitive to contact
- Complex shape (pyramidal structure, round shapes, cube shape >6 surfaces)
- No features to help the joining, handling, or feeding process
- No surface, feature available that can serve as datum point or surface
- Necessity for bio-compatibility of materials to be used

After analysing the part characteristics and assessing the complexity of the parts, it is advisable to redesign the product by changing *too simple* (=C1) or *too complex* parts (=C6). DFμA guidelines should be considered in order to improve the conceptual design. A number of *too simple* parts indicates that there is room to improve the design efficiency, i.e. the parts could be integrated into other parts or could take on additional functions (see Figure 50). The presence of *too complex* parts can be understood as indicating the potential for problems to occur during the microassembly process. Excessively complex parts should be redesigned to reduce complexity. For example, this could be done by splitting them into several parts that are easier to handle, feed, or join, or by taking out functions and integrating them into the joining medium. The functions are captured to establish the *functional design efficiency*, which is taken from the *Lucas DFA method* (see section 2.5.3).

The idea of functional design efficiency could be taken as a guide for microproducts as well. However, when making adjustments in MST, a greater degree of consideration should be given to issues pertaining to the parts' complexity. Finally, it should be noted that the complexity analysis is applied to *pre-screen* a design alternative before spending more time and effort on it. As a result the improvements on conceptual design lead to an optimised embodiment design.

5.3.3 Process-product analysis and microassembly routes

For all that the *complexity analysis* will have optimised the conceptual design, it remains possible there will be no appropriate microassembly processes available to realise the embodiment design. It is for this reason that the designer should be aware of the possibilities and limitations of the assembly processes, in order to consider them when designing the components in more detail. Accordingly, the process-product analysis should be carried out as soon as possible, to allow for the early adaptation of the product design. It is therefore critical to capture the process-related product characteristics to enable the selection of suitable processes. The influences of the microassembly processes have to be constantly kept in mind. The detailed microassembly process data are provided by the microassembly capability model (see section 4.4, the *process characterisation element*). In accordance with these data product features can be designed and optimised, and processes for the equipment modules defined (see Figure 47 and Figure 51).

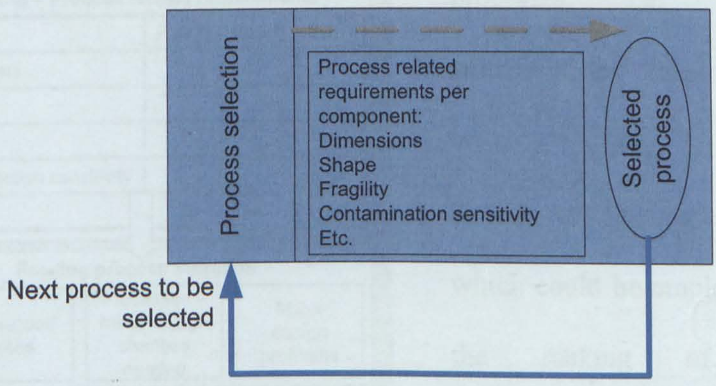

Figure 51: Process-product analysis and microassembly process selection

The following use cases of the DFμA environment are represented in the *process-product analysis and microassembly process selection* phases (see Figure 43):

- Provide assembly capabilities
- Capture the data related to the embodiment design
- Analyse product against assembly process capabilities
- Evaluate qualitative assembly process costs

- Select assembly processes

Figure 52 gives an illustrative example of how the *process-product analysis* is structured. Based on the design already improved in earlier stages, the assembly processes, namely feeding, handling, joining, and inspection, are chosen. In the instance displayed, the selection of feeding processes is described. First, all parts to be fed are selected. Then, process-related product requirements and part properties (like dimensions, shape, fragility, sensitivity to contamination etc.) are retrieved.

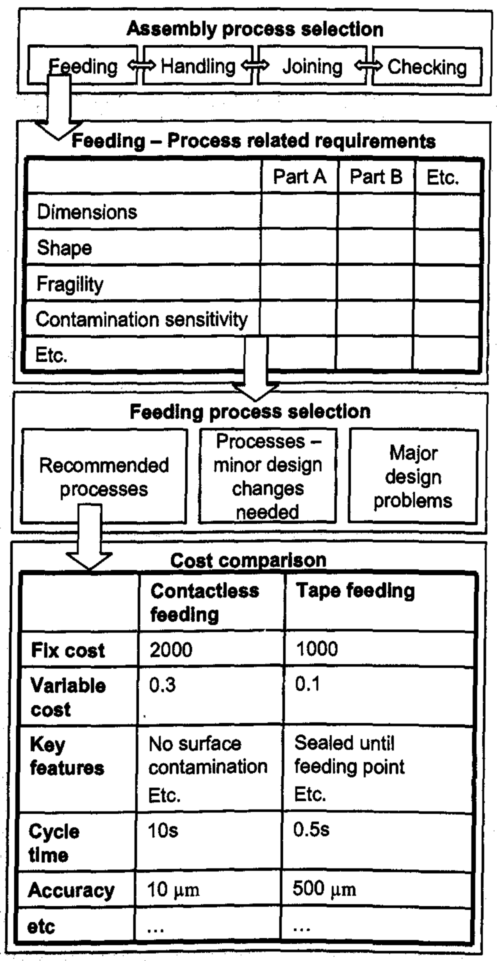

Figure 52: Process-product-analysis – Selecting a feeding process

Using this information results in:

- A list of recommended feeding processes, i.e. processes suitable to the design as it now is
- A list of feeding processes which could be employed with the making of minor modifications to the design (including indications for design improvement)
- The excluding of a number of feeding processes, because of incompatibility with the process-related product requirements

The features that make the DFμA unique, distinguishing it from conventional DFA approaches have already been implicitly described in this chapter and can be summarised as follows:

The procedural methodology has been developed as part of a holistic approach, utilising the new microassembly capability model and providing for the applying of DFμA guidelines. As mentioned before, conventional DFA methods by no means meet the specific requirements of the assembly-oriented design in the microworld. Figure 53 summarises the limitations of existing DFA methods addressed in the development of the overall DFμA methodology. It also displays the advancements offered by the DFμA methodology presented here.

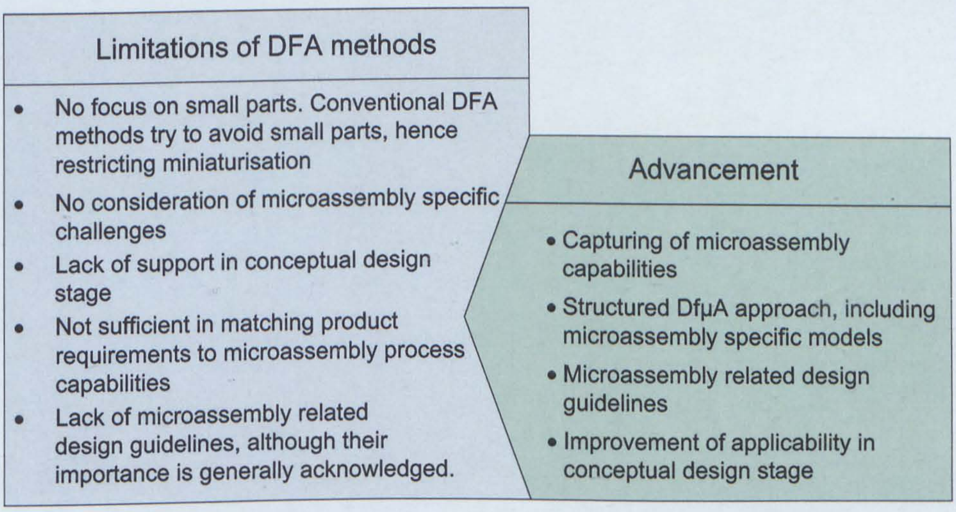

Figure 53: DFμA methodology development – overcoming current DFA limitations

The overarching DFμA methodology presented in this chapter distinguishes itself from existing DFA methods because it supports the matching of process and design features, therefore providing support for process selection (e.g. *product-process analysis*).

In addition, to meet the microspecific requirements as elucidated in Chapter 2, a novel complexity analysis has been developed and introduced to make the

DFμA methodology usable in the conceptual design stage. The importance of assessing the complexity of microproducts and their parts is generally agreed upon, however there is so far no means of analysis available to do this in microassembly. The complexity analysis can be understood as a significant contribution to the existing body of knowledge in microassembly as it is the first attempt to capture and quantify products' complexity while considering assembly-orientation.

6 DFµA guidelines

"Design guidelines are one of the main sources of explicit knowledge on the practice of design" (Edwards, 2002).

The previous chapter having explained and discussed the overall DFµA methodology, this chapter deals with microassembly guidelines provided to support the designer in finding optimised product functions with consideration to microassembly constraints.

The results of a guideline analysis and definition focussed on both the product and the assembly process side are outlined. The process-related guidelines and recommendations are linked to the assembly capability model (see section 4.2). The guidelines aim at enabling assembleability. Moreover, they result in a range of benefits such as reduced development and assembly cycle time, the re-use of existing processes, higher quality due to adaptations in the product design with respect to process selection and layout, and a reduced time to market. These various benefits arise out of the various ways, areas, and phases in which the guidelines can be consulted: from directing the product design process to process selection and optimisation.

Such guidelines for microassembly are particularly needed because paying too little attention to assembly-related aspects in the design stage often results in failure of the product. Since microassembly forms a substantial part of the production cost (see section 2.3), it is important to ensure that designers *plan for production.*

The chapter is structured as follows. First, the fundamentals and relevance of design guidelines within DFμA are highlighted (section 6.1). Section 6.2 explains the approach for the analysis of existing conventional product design guidelines, and the main findings of the analysis are critically discussed. In section 6.3 microassembly process-specific guidelines are explained. As well as *defining* guidelines it is important to *consider their application* within the overall DFμA methodology (see section 6.1.3). Using the phase model introduced in section 5.2.3 (see Figure 47) it is shown how and where the guidelines can be applied. Means of applying these guidelines are discussed and defined.

6.1 Approach to the generation of design guidelines within DFμA

Guidelines generally contain information about appropriate methods for implementing requirements related to processes, procedures, work instructions, etc. This section aims at outlining the development of an approach for the generating of DFμA guidelines. The following subsections describe the relevance of guidelines within microproduct design (section 6.1.1), and explain the role they play within the DFμA concept (section. 6.1.2). Finally an overall approach to creating guidelines is developed (section 6.1.3).

6.1.1 Relevance of guidelines in the microdomain

The overall objective of manufacturing guidelines is to describe how to reduce *time, cost,* and *effort* while increasing *quality* in the fabrication of a product (see Figure 54). Traditionally these goals were seen as often competing: quality improvement and decreased cycle or throughput time were thought to result in higher costs, while cost savings were understood as made at the expense of production quality and cycle times. Now this understanding has changed: quality management and improved cycle or throughput times do not necessary lead to increased production costs. Furthermore, cost savings do not automatically have an impact on product quality and production time.

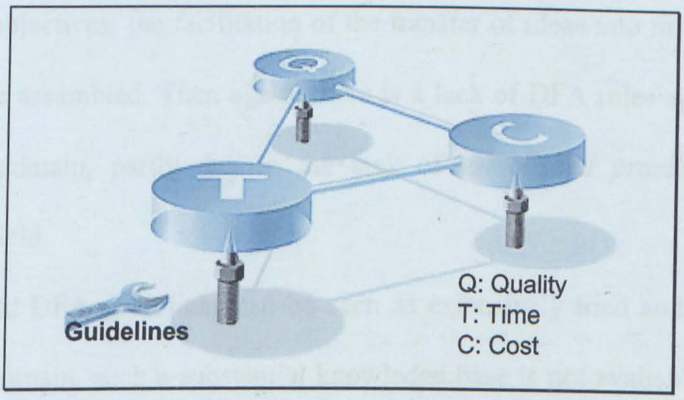

Figure 54: Effects of guidelines – cost, time, and quality (adapted from Siemens, 2007)

The FMEA is an instrument commonly employed to analyse *failure possibilities* and to reduce their *probability* as well as their *impact* before the production stage.[13] Results of such analyses can be translated into guidelines to continuously improve the process of product and production development, resulting in the avoidance of these mistakes when designing new products.

Design guidelines are often domain-specific, representing a canon of experience in applying existing technology in the particular area. EDWARDS identified the following as the main sources of design guidelines (Edwards, 2002): literature, direct experience of practicing designers, and established design principles in engineering organisations. Naturally, those last two are much more difficult to access than the literature.

[13] It is also common to use FMEA during the production stage. Accordingly it can be distinguished between Design- and Process- FMEA.

Because of the potential for making improvement that is inherent in any new industry, there is a real importance attaching to the developing of guidelines for microproduct development and microassembly, maturing areas under constant technological development.

Within DFμA, increasing the assembly quality and its predictability is one of the main objectives: the facilitation of the transfer of ideas into microproducts that can be assembled. Then again, there is a lack of DFA rules applicable to the microdomain, partly due to the lack of *established practices* in this maturing field.

Macroworld DFA guidelines can be seen as extensively tried and tested; for the microdomain, such a substantial knowledge base is not available yet. This is one of the reasons for the lack of transfer of research prototypes to industrial practice (see section 3.1.2).

Besides fulfilling the functional and working interdependencies, a solution has to comply with general or task-specific constraints and requirements such as reliability, production, quality control (during the design and production process), assembly (during and after the production of components), transport, operation (planned use), maintenance, expenditure, and recycling (Pahl *et al.*, 2007, Hubka and Eder, 1992, Hubka and Eder, 1988). Characteristics derived from these constraints or requirements should be treated as guidelines throughout the design process.

There are instances in which classical DFA guidelines do not provide a best fit for the microdomain. For example, in conventional DFA reducing the number of parts is seen as one of the key objectives. This can *sometimes* be advantageous in the microdomain, but it can in many cases be useful to substitute one complex part characterised by handling difficulties with several parts that are easier to handle (see section 5.3.2). What is further true is that the extremely small sizes of components in microassembly and the requirement for absolute accuracy leave some classical DFA recommendations with regard to low tolerances inapplicable here.

6.1.2 Role of DFμA guidelines within the overall concept

Having described the relevance and importance of DFμA guidelines it is necessary to define their role within the DFμA methodology. This section discusses requirements for DFμA guidelines and ways of classifying them. Naturally, these guidelines have to provide for these requirements derived from the challenges inherent to MST products and microassembly (see sections 2.3 and 2.4).

An *Ishikawa diagram* which represents in terms of causes and effects the microassembly failure of a product design has been developed and is presented in Figure 55. That diagram is informed by:

- The literature review detailed in Chapter 2, and in particular by the findings of the analyses with regard to the challenges and assembly processes in the microworld as given in sections 2.3 and 2.4
- An organised microassembly workshop
- International conferences
- Practical laboratory experience

Figure 55 shows the main categories identified, spanning the DFμA-related problem space:

- Product design

  Product design-related guidelines are of a more general nature and do not directly depend on certain microassembly processes. They are mainly dependant on the functional product requirements. However, there are also general recommendations which can be taken into account by the design team regardless of the desired product function.

- Processes

  There are guidelines that enable the use of specific microassembly processes, for example by suggesting a certain shape or material to better join or position the part. These guidelines are called *process-related guidelines*. A lot of these guidelines use the information provided by the assembly capability model (see section 4.2).

- Milieu (environment/universal requirements)

  The third category deals with general problems related to the natural environment, and to the economic and technical context in which the company is placing its production operations. This category is called *milieu*.

Figure 55 clearly demonstrates the complexity of the problems occurring on product and process design levels in microassembly. Furthermore, it captures the issues that need to be addressed by guidelines. These problems form the basis for the analysis of existing DFA guidelines (section 6.2) and are considered for the development of novel DFμA guidelines (section 6.3). The following subsection describes a universal approach toward developing design guidelines for DFμA in a scientifically accurate way.

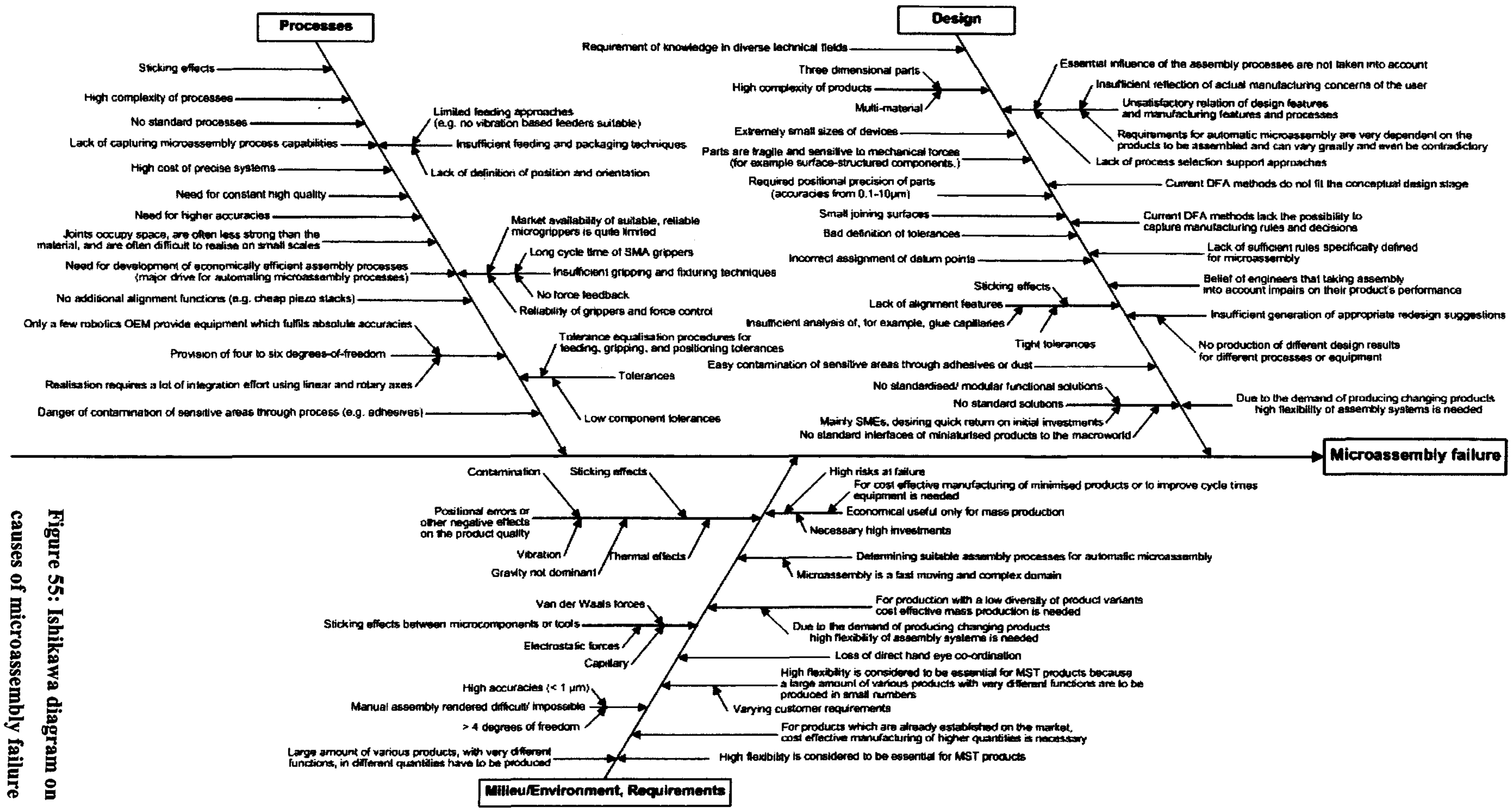

Figure 55: Ishikawa diagram on causes of microassembly failure

6.1.3 General approach to DFμA guideline development

After highlighting the causes and effects of microassembly failure (see Figure 55), it is clear that guidelines need to be developed to address them. Currently there is a lack of generally accepted guidelines. From a scientific point of view it is important to create a plausible and logical method for the development and evaluation of DFμA guidelines.

The following have been identified as means to create a set of DFμA guidelines:

- *Transfer* the existing DFA guidelines from the macroworld, after initial investigation of feasibility
- *Adapt* guidelines from the macroworld according to the specific microworld challenges, microassembly processes, and demands for automated microassembly
- *Develop* new guidelines according to microspecific requirements and on the basis of experience gained from microproduct assembly and design within industrial practice

A model on how to *transfer, adapt, and develop* guidelines contributes substantially to the research but also to the industrial community, securing a consistent approach and building up a base of DFμA guidelines so that designers can rely on these existing experiences. An analysis has been carried out to examine existing DFA guidelines with regard to their *transferability*. Some of these guidelines are *adapted* and novel DFμA guidelines have been *developed.* These guidelines have to be empirically tested and proven and continuously improved upon.

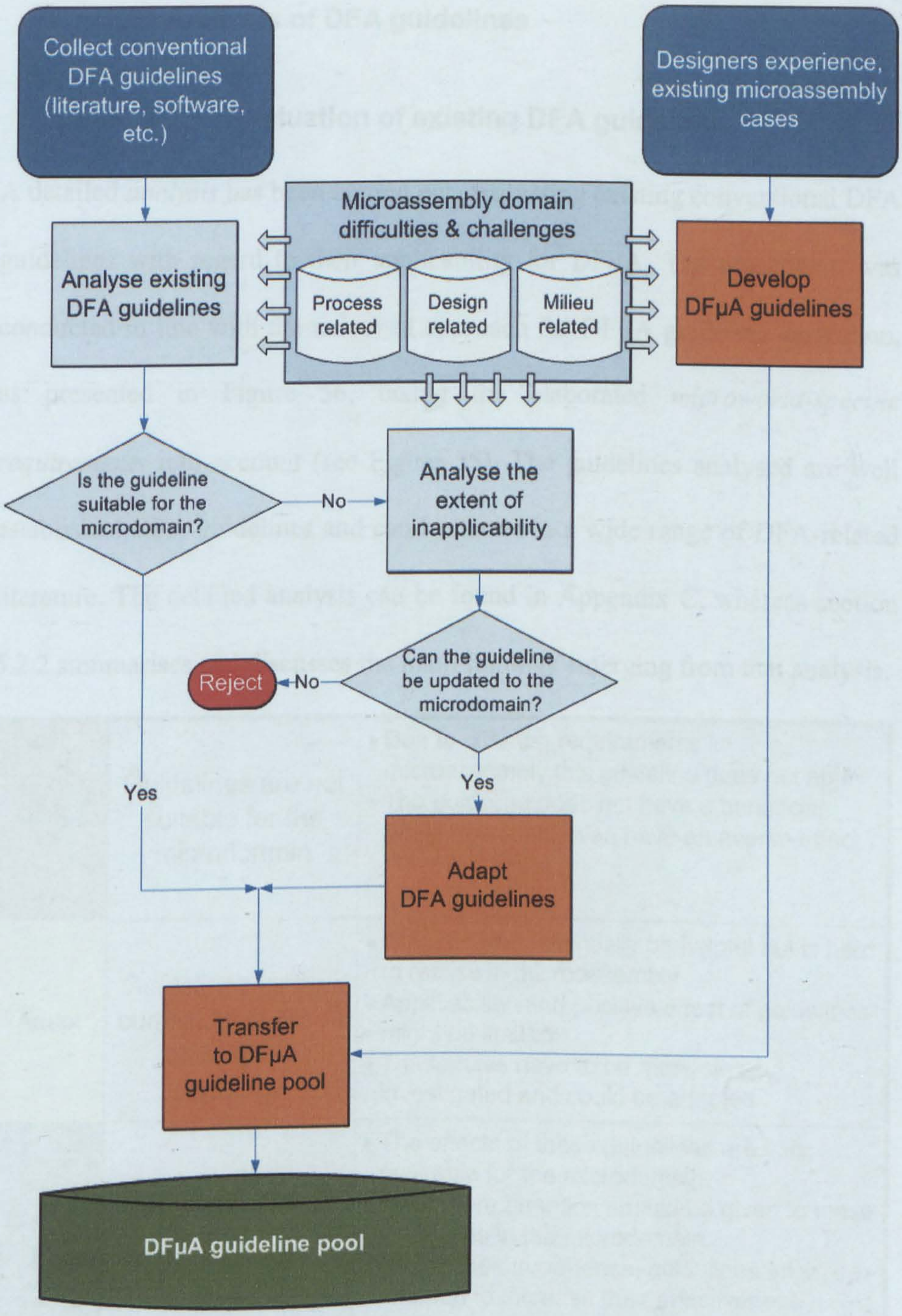

Figure 56: Universal approach to DFμA guidelines generation

6.2 Analysis of DFA guidelines

6.2.1 Evaluation of existing DFA guidelines

A detailed *analysis* has been carried out, evaluating existing conventional DFA guidelines with regard to their applicability for DFμA. The assessment was conducted in line with the universal approach for DFμA guideline derivation, as presented in Figure 56, taking the elaborated *microworld-specific requirements* into account (see Figure 55). The guidelines analysed are well established DFA guidelines and can be found in a wide range of DFA-related literature. The detailed analysis can be found in Appendix C, whereas section 6.2.2 summarises and discusses the main findings emerging from that analysis.

Reject	Guidelines are not suitable for the microdomain	• Due to differing requirements in microassembly this guideline does not apply • The guideline does not have a beneficial effect and could even have an averse effect
Adapt	Guidelines in their current form are of limited help	• Advice could potentially be helpful but is hard to realise in microassembly • Applicability and positive effect of guidelines might be limited • These rules have to be more closely investigated and could be adapted
Transfer	Guidelines seem to be particularly useful	• The effects of these guidelines are very desirable for the microdomain. • Even more attention should be given to these guidelines in the microdomain. • Due to their importance, guidelines might be adapted to increase their effectiveness

Figure 57: Evaluation of existing DFA guidelines

The guidelines have been broken down and their benefits investigated and classified using colour-codes (see Figure 57). The groups collect guidelines:

- That are not suitable for DFμA (*Reject*)
- That have only limited applicability in their current form (*Adapt*)

- That are particularly useful within the microdomain (*Transfer*)

Useful DFA guidelines, conferring beneficial effects, are either transferred to a pool of DFμA guidelines in their current form, or might be changed to enhance their effects if they are understood as being of particular importance. In the analysis these guidelines are marked green.

Guidelines characterised by limited applicability are adapted because they could potentially be helpful but are difficult to realise in their current form in microassembly. Furthermore, it can be the case that the guidelines are only helpful in certain situations. These guidelines are colour-coded yellow and need to be made subject to closer investigation.

Other DFA guidelines have to be disregarded for microassembly due to the different requirements obtaining in the microdomain. These guidelines do not have a positive impact on assembly-oriented microproduct design or could even have adverse effects. In the analysis these guidelines are colour-coded red.

Table 6: Extract from DFA guideline analysis

Category:	Breakdown of conventional DFA guidelines	Applicability in DFμA
Minimise handling	To facilitate orientation symmetrical parts should be preferred wherever possible.	Reducing complexity is important in the microdomain. However, it can be difficult to realise symmetrical parts when the objective is to miniaturise parts.
	Use external guiding features to help the orientation of the part.	Due to sticking effects the use of classical external guiding features (contact-based) is difficult. However, tailor-made solutions (e.g. V-gooves for glas-fibre cable alignment or self-alignment approaches) are possible. Batch feeding and parallel assembly due to larger substrates can utilise such guiding featurs too.
	The subsequent operations should be designed so that the orientation of the part is maintained.	Extremely important. Gripping and releasing is a difficult task in microassembly. A basic rule should be to 'never lose orientation of a part.'
	Also magazines, tube feeders, part strips etc. should be used to keep this orientation between operations.	Extremely important, particularly magazines seem to be a suitable feeding approach. However, there are no standards and they have to be tailor-made for each component.

Table 6 shows an extract of the DFA guideline analysis, dealing with the category *'minimise handling.'* It is broken down to detailed conventional DFA guidelines (second column). The third column contains the assessment with regard to the applicability of each guideline in the microworld. Two guidelines were identified as unsuitable for the DFμA (colour-coded red) and two were classified as extremely important for the microdomain (green). The following section deals with the findings of the analysis, and outlines areas that need to be carefully investigated in assembly-oriented microproduct design.

6.2.2 Findings of conventional DFA guideline analysis

It is necessary to analyse existing DFA guidelines and the different technological topics they cover and to investigate their applicability to microassembly before developing novel DFμA guidelines.

A comparison of conventional DFA guidelines with the demands and requirements for microproducts has been conducted. The macroworld guidelines have been broken down and then analysed with regard to their suitability. The detailed analysis of existing guidelines can be found in Appendix C. It was carried out according to the procedure explained in the previous section. The main results of that analysis are summarised as follows.

> A large proportion of the macroworld design guidelines are valid in the microworld and can be *transferred.* Due to different general conditions, the focuses of some guidelines need to be moved and others need to be *adapted.* Some conventional guidelines are not applicable in the microworld and so are *rejected.* In order to make good the shortfall created by the rejecting of these rules, novel DFμA guidelines need to be *developed.*

The following issues are of critical importance in the microworld:

- *Design focuses on functionality, no standards available*

  Designers of microproducts do not derive their ideas from already existing solutions that seem similar. They most of the time have to design their solutions from scratch, so the having of unnecessary parts or elements is highly unlikely, whereas this is often the case in the design of conventional products. Moreover, it is important to investigate the whole system because considering only the functioning of the individual components does not lead to adequate solutions.

- *Reduced complexity*

  Sticking effects, tight tolerances, etc. increase the complexity of the product assembly process (cp. Section 2.4). Therefore, it should be made a focus of the design to limit the complexity of both the assembly system and the product and part design in order to avoid failures and increase reliability (see section 5.3.2). In more detail, this means (see Figure 58):

  - Increase functional integration wherever possible
  - Split parts (thus decreasing their complexity) to avoid handling difficulties
  - Analyse the tolerance chain, including the component tolerances resulting from the manufacturing processes and the assembly tolerances resulting from feeding, handling, and joining

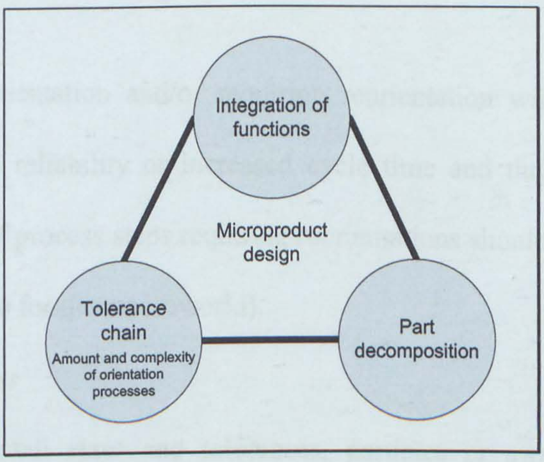

Figure 58: Conflicts in microproduct design

- *Design, fabrication, and assembly are closely related*

  The question is not '*how* to manufacture a product?' but more importantly '*can* the product be manufactured and *assembled?*' In the macroworld these questions are often asked and answered by different people at different phases in the design process. In the microworld this needs to be done *simultaneously.*

- *Handling is of critical importance*

  Within production and assembly, handling, that is positioning and gripping, remains a critical process. Material properties of the product components and the gripping mechanisms and their relation to environmental conditions have to be considered (see section 6.3.5 on gripper design). The effects of these (e.g. temperature or humidity) can make it necessary to very closely control the environment.

  The principles of *PokaYoke*[14] should be applied if necessary and

[14] *PokaYoke* is a quality management principle developed in Japan. It aims at failure prevention and discovery through simple technical measures. A fundamental principle is the lock-and-key principle. That means quality is designed into a product and its parts by making failures impossible.

possible.

Losing orientation and/or requiring reorientation will lead to either decreased reliability or increased cycle time and thus is costly. The number of process steps requiring reorientations should be limited (this is also true for the macroworld).

- *Cleanliness*

  Due to small sizes and tolerances, particles or swarf can lead to misalignments or functional failures (e.g. current conducting small pieces could cause short circuits). Accordingly, clean room environments become necessary, driving up production costs.

- *Reliability*

  Measurement and process capabilities are very important. Indices such as c_p and c_{pk} need to be considered. Because it is very difficult to get these values (due to the immaturity of microassembly technologies and case-specific applications, see section 2.3), it is even more important to run machine capability tests when setting up the assembly system to learn about the number of defective parts (probability of defective parts) and so be able to put inspection methods in place (probability of defect discovery). In addition, it is very important to define part and process tolerances accurately.

As expressed above (see point '*Design, fabrication and assembly are closely related'*), in the microworld it is even more important to work on process and product design in parallel/simultaneously than is the case in the macroworld. *Know-how of design and production with specific regard to microassembly needs to be connected.* These parallel developments require close coordination of assembly technology and product design in order to fully exploit the possibilities of MST (see section 5.2.3). *In that context the following additional points have been identified as problematic for DFμA guidelines because the microworld requires different techniques here:*

- *Fasteners*

  The state-of-the-art with regard to joining and fastening has been introduced in section 2.3.4. The most important joining mechanisms in microassembly are based on adhesives. It is essential, then, to collect adhesive-based joining guidelines (see section 6.3.6). Further, there is a need for research in the area of gluing microproducts, for example capillaries in the design of the joint could be analysed more closely resulting in better utilisation.

- *Fixtures*

  Fixtures are important in the microdomain because precise alignment and location accuracy of workpieces are crucial to the success of microassembly processes. Fixtures need to *save* the current part orientation and are not allowed to exert high forces on the components because of the risk of damage and misalignment.

- *Tactile processes*

  Under certain circumstances they should be substituted by optical processes (quality assurance).

It has been pointed out that there are gaps in current DFA guidelines which have to be addressed by the development of novel microspecific guidelines. The outcomes of the DFA analysis led to the definition of critical aspects for DFμA. A selection of essential DFμA guidelines is presented in section 6.3.

6.2.3 Product-, process-, and milieu-related guidelines

Product design guidelines

A good example of adapting the product design to ease microassembly, and thereby address a whole range of requirements analysed in section 2.4.3, is related to the accurate placement or alignment of components. To reduce costs and improve the process quality, the use of self-alignment structures and methods is advised because this reduces the required handling process accuracy. Section 6.3.2 provides detail regarding the self-alignment techniques and methods important for microproduct design. Other alignment techniques are based on feedback, e.g. based on visual information. For such an approach it seems useful to integrate external part features with the parts in order to support their alignment (see section 6.3.3).

Process-related design guidelines

Systems for automatic microassembly are dependent on a range of requirements, utilising knowledge from various disciplines (see section 2.4.3). Designing such systems means integrating different microassembly processes. It is clear that the nature of the product to be assembled has a strong impact on the assembly system (see section 2.2.1). Certain guidelines influence the product design based on the chosen assembly process and vice versa. For example, it is advisable to adapt either the grippers according to the product geometry or certain part features to the gripping principle. Because gripping is such an important but difficult process in microassembly, specific design guidelines are collected (see section 6.3.5). These process-related guidelines can be based on or can use the information provided to the assembly capability model. Naturally, the more process providers fill in the process sheets (see

Figure 39), the more commonalities can be identified and the more guidelines can be provided.

Milieu-related guidelines

The milieu-related guidelines are required to tackle the specificities of assembling in the microworld. These requirements are derived from the challenges which are inherent to both the physical and economic environments. The following are the issues mainly targeted by milieu-related guidelines:

- Physical boundary conditions:

  Contamination, sticking effects, thermal effects, vibration, etc.

- Economic boundary conditions:

  Manual assembly is rendered impossible; large amounts of different products in different volumes require flexible assembly solutions; fixed automation is desirable for established products; high investment cost leads to high economic risks.

6.3 Microassembly-specific guidelines

For the development of DFμA guidelines two main objectives have to be considered. On the one hand, weaknesses in the current product designs need to be identified; on the other hand, hints should be given to facilitate better solutions. The following subsections describe actual DFμA guidelines and areas needing attention from a microassembly point of view. A comprehensive pool of guidelines has been generated and can be found in Appendix D.

6.3.1 Maintenance of orientation

In microassembly it is not enough merely to *know* the current component orientation, what is recommended as well is that this orientation should always be closely controlled. If the orientation needs to be changed, e.g. the part has to be transported to the next station, this should always be done by constraining the part. In particular, releasing (e.g. opening of gripper) and gripping (e.g. gripper closure) are critical processes, because sticking effects might cause a change in orientation as explained in sections 2.3.2 and 2.4.1. When the holding mechanism releases a component it should be secured already by another mechanism, e.g. *when joining, hold the component in place until the glue is cured.* In this way the sticking effects can be prevented from disrupting the assembly, because pre-empted and policed throughout the whole process chain (guidelines on how to reduce the actual sticking effects are described in section 6.3.4). Every required change of orientation is accompanied by a risk of losing the desired orientation or losing the exact information regarding the orientation. Accordingly, the number of orientation changing operations should be kept to a minimum.

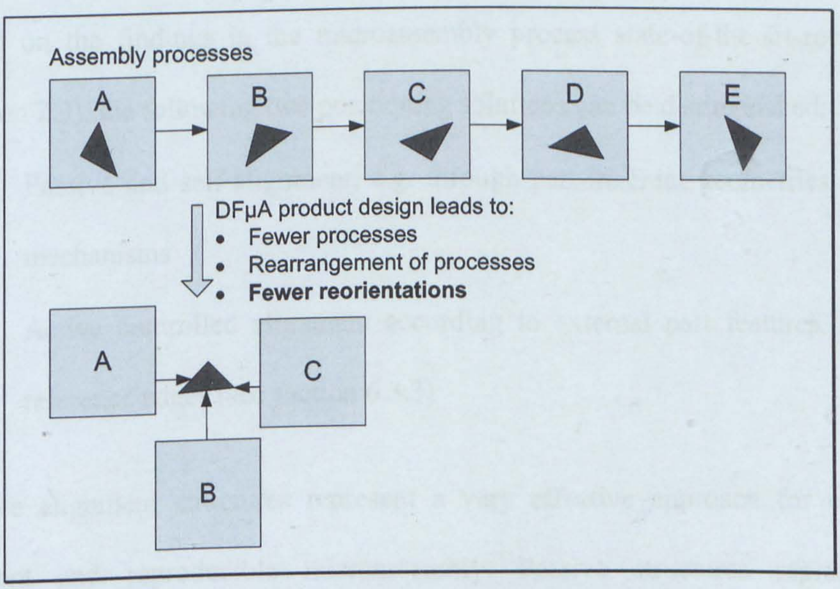

Figure 59: Guidelines – do not lose orientation and reduce process steps

Figure 59 indicates that assembly-oriented microproduct design should aim at a product structure that reduces the number of processes in/for which reorientation is necessary. Furthermore, it illustrates that the assembly processes should be selected in such a way that the product to be assembled is at the centre, with the required processes clustered around it. The reduced need for the product to change position or be reoriented leads to certain benefits in terms of reliability:

- Reduced risk of misalignment (caused by sticking effects)
- Reduced possibilities of losing orientation (which would render gripping and joining impossible)

Another challenge is to detect the orientation once it is lost. The resolution of conventional macroworld sensors is in the microworld often insufficient for this purpose. In addition, to avoid misalignment, no high forces should be exerted on the components.

6.3.2 Self and passive alignment

Based on the findings in the microassembly process state-of-the-art-review (section 2.3), the following two positioning solutions can be distinguished:

- Passive and self-alignment, e.g. through part-inherent geometries and mechanisms
- Active controlled alignment according to external part features, e.g. reference edges (see section 6.3.3)

Passive alignment structures represent a very effective approach for cost-efficient and reproducible microassembly. Passive structures represent mechanical stops or elastic elements which position or align the microparts in accordance with the required accuracies. They are characterised by tolerances of only a few micrometres (Brecher *et al.*, 2006). V-grooves, for example, are commonly used to align glass-fibres, see Figure 60.

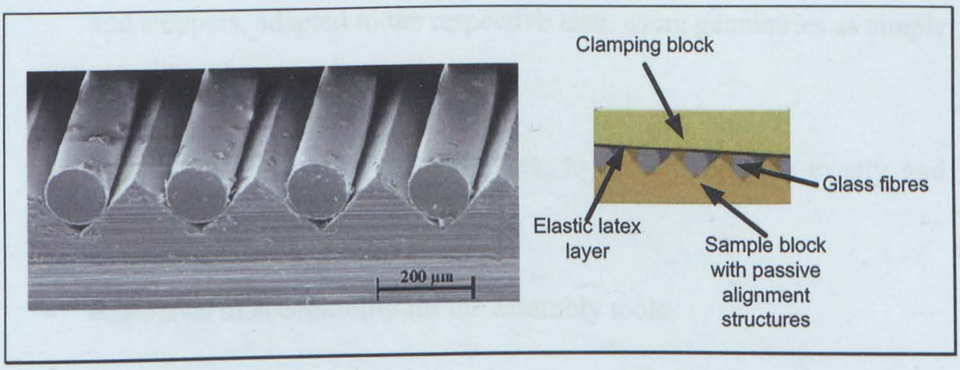

Figure 60: Passive alignment of glass fibres (Brecher *et al.*, 2006)

Self-alignment mechanisms are in general based on defined geometries. The components to be assembled are characterised by matching features on both parts (Scheller 2001). Basically, one part contains a positive feature whereas the second part holds the negative feature. Although this principle is known from conventional assembly, for the microdomain it provides even greater benefits. This solution allows the using of less accurate handling processes, which in turn decreases the system cost whilst increasing its efficiency. However, in the microworld these features cannot rely on gravity alone. The assembly system needs to provide a degree of force to bring the mating parts into position. Other dominant forces such as capillary forces can be exploited by adding liquid or features to the part. Of course the alignment features need to be manufactured accurately to allow the desired precision. In addition, the geometric complexity and size of the component influence the accuracy. SCHELLER states that self-alignment procedures can achieve axial accuracies in the range of a few micrometres and rotary accuracies of lower than 1°. However, the following requirements have been formulated to improve the self-alignment process (Scheller, 2001):

- Development of alignment mechanisms with defined negative forms and stoppers, adapted to the respective task, using geometries as simple as possible
- Integration of cavities for adhesives, to spread the glue evenly and avoid component contamination
- Assurance of accessibility for the assembly tools
- Integration of principles for positioning support during the assembly process, to realise a defined position and orientation of the components to be mated

Although such guidelines can be used in isolation, the objective of the research described here is to integrate such guidelines in the bigger scheme of the DFμA methodology. Section 6.4 shows how these guidelines can be represented and how they can be applied and implemented within the overall DFμA methodology.

6.3.3 Controlled alignment to external part features

Assembling without self-alignment features results in a direct dependency on the whole tolerance chain of the assembly and part manufacturing processes. To ease this dependency or allow bigger manufacturing process variances for the components, it is necessary to align and position the parts in a defined and controllable way (Scheller, 2001).

Components' positioning can be controlled with reference to external part features (e.g. geometry or pattern) by measuring them with an image processing system (different measurement methods such as capacitive, inductive, or tactile sensing could also be used). The resulting difference of nominal/actual value comparison within the spatial coordinate system is used to control/regulate the assembly process. Requirements to improve the described alignment process based on external features can be formulated as follows (Scheller, 2001):

- Detectability of components and their alignment features during the assembly process
- Illumination of the components to realise sufficient contrast, necessary to allow for recognition of edges and sufficient measurement accuracy (when employing visual measurement systems)
- Use of positioning processes sufficiently accurate to align the components according to the target values

6.3.4 Reduction of sticking effects

Sticking effects have been identified as one of the main causes of failure in microassembly (see section 2.4.1), particularly in the gripping and releasing processes (see section 2.3.2). A range of approaches can be taken to reduce these effects. YEH AND SMITH suggested immersing the assembly process in a fluid, thus eliminating any surface tension and electrostatic effects (Yeh and Smith, 1994). Their approach is used in the context of self-assembly, but because of the contamination of functional surfaces it is seldom appropriate. More applicable strategies to overcome adhesive effects are listed below (Böhringer *et al.*, 1999, Fearing, 1995):

- Contact electrification can be reduced through using materials with small contact potential difference
- Using conductive materials reduces electrostatic effects

- Contact surfaces should be kept to a minimum (e.g. rough surfaces, round contact points instead of areas)
- Hard materials are favoured over rubber and plastic due to a reduced likelihood of the deformation that can lead to increased surface area
- Surface tension effects can be reduced by providing a dry atmosphere

These rules are very generic. As stated, the moments of gripping and releasing microparts are seen as critical. That is why a more detailed analysis including guidelines on the gripper design is given in the following subsection.

6.3.5 Optimisation of microgripping

Developing and selecting adequate microgripping principles depends on certain criteria that have to be considered in terms of their applicability to a particular micropart. It is important to consider factors coming from the part itself, the necessary gripping orientations, and the milieu in which the process takes place. The gripping process depends on factors such as material type, surface properties, gripping forces, force control, shape of interaction surface, cycle time, accuracy of gripping and gripper movement, sensitivity to adhesive forces, assembly environment, and so on. The first step is to choose a principle. The next step is the technical design of a gripper, conducted with reference to the criteria listed above (Tichem *et al.*, 2004).

Section 6.3.4 introduced general guidelines to reduce sticking effects. The list below provides more detail related to means of overcoming sticking effects when releasing a part (based on Bark et al., 1998, also cited in Van Brussel et al., 2000):

- Consider part features that support self-alignment when using adhesive bonding to accurately glue the component into the right position.
- To mechanically release the object by locking it to the substrate or by stripping it off against an edge (Zesch *et al.*, 1997), or by using needles. In order to push the object a suitable element needs to be considered in the part design.
- When vacuum gripping is envisaged gas can be injected: gas pushes the part while taking away the gripper. Therefore a flat and stable surface needs to be designed into the parts to be handled (by vacuum grippers).
- When utilising surface tension force to grip a part, it can be released by evaporating the adhesive liquid. To realise this, components have to be designed accordingly, i.e. for example heat-conducting materials have to be selected.
- Design the parts in a way that adhesion effects can be utilised: the adhesion between the substrate and the object must exceed that between the microgripper and the object, e.g. through appropriate part shapes or surface roughness (Cohn *et al.*, 1998, Zesch *et al.*, 1997).

To enable adequate gripping of microcomponents and their attachment to the workpiece in the desired orientation, it is necessary to create a *"hierarchy of adhesive forces"* (Cohn *et al.*, 1998): adhesive forces between the component and the open gripper jaw surfaces should be lower than the adhesive forces between the component and the substrate. In this way the part's jumping to the gripping device and therefore loss of orientation is avoided (see guidelines in section 6.3.1).

6.3.6 Joining with glue

Due to its positive properties, gluing is typically the most appropriate joining solution in microassembly (see section 2.3.4). In terms of microproduct design, the different properties of glue can be used to integrate functions into joints, and thus into the products, without the need for additional parts. The main functions can be categorised into the elementary functions of *conducting* and *insulating*. Dependent on the adhesive type or by using existent filler particles, it is possible to integrate the following functions (based on Dorfmüller *et al.*, 2007):

- Structural support or damping by means of adhesive layers (regulation of tension)
- Conduction or insulation of electrical current
- Conduction or insulation of heat
- Adhesives can be transparent for light of certain wave lengths of or can be entirely opaque
- Glue can be used for sealing
- A few adhesives may also provide a certain degree of permeability for gases

Increasing adhesive layer thicknesses improves these functions. However, when joining the parts with glue, self-alignment as described in section 6.3.2 can be problematic, because the accuracy of the glue joint can suffer from the force exerted by the assembly system (sliding of the parts on the glue cushion). Therefore, it is important when using glue to control both the volume of glue dispensed and the force exerted to make the joint.

6.4 Application of DFμA guidelines

In section 5.3 the *phase model* as part of the DFμA methodology has highlighted the iterative process leading to a microproduct design that not only fulfils the functional requirements but is also assembly-oriented through its utilising the DFμA guidelines and considering process characteristics (see Figure 47). Using the guideline classification introduced in section 6.2.3, different application phases that correspond with the overall DFμA are identified in Figure 61. DFμA guidelines are applied to the conceptual product design within the early design stages (see section 2.2). The product-related design guidelines are available for consideration by the designer during or even before the creating of the first conceptual product design. Typically, the designers are not aware of any assembly processes for the product at this stage, let alone the consequences that the selection of individual processes might have. With guidelines made available to them, the designers are able to gather a general understanding of DFμA.

As explained earlier, microassembly is a maturing industry, characterised by a high rate of technological progress (see Figure 6), it is therefore necessary to monitor these advancements and utilise them within the product development process. According to the distinction of *process-* and *product*-related microproduct design guidelines, the product design is adjusted to the selected assembly processes, and the processes as well are optimised relative to the final product/component designs. Furthermore, it is important to consider the envisaged production environment; that is to say, *milieu*-related guidelines have to be applied as well.

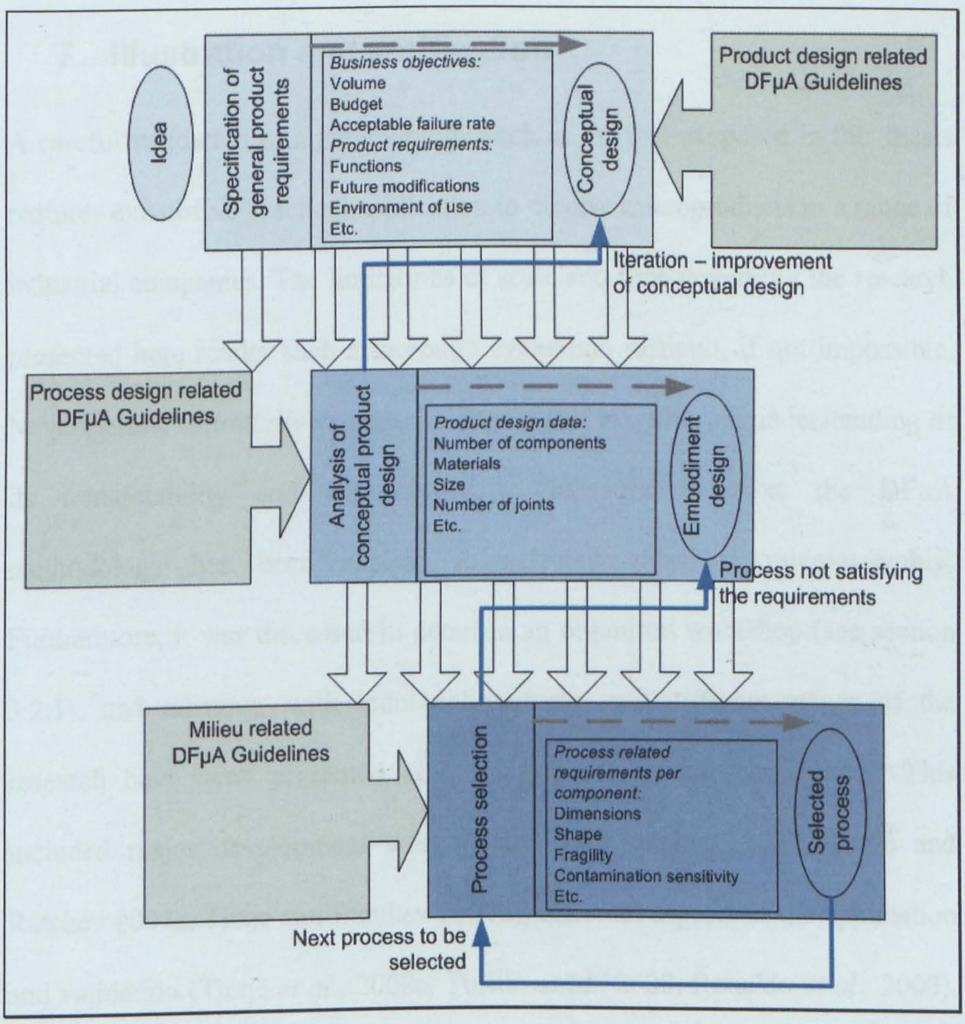

Figure 61: Phase model of application of guidelines

A way of implementing DFμA guidelines is the use of *checklists*, which can be used by the designer to determine a product design's weaknesses or flaws in a systematic way. A major advantage is that checklists can be easily applied and customised in a range of different industrial areas according to a company's needs and containing appropriate decision-relevant characteristics. Appendix D presents a comprehensive pool of DFμA guidelines which are based on practical experience and theoretical analyses and which can be easily translated into checklists in the form of questions or recommendations.

7 Illustration and verification

A careful validation of a methodology such as the one proposed in this thesis requires exhaustive practical application to diverse microproducts in a range of industrial companies. The limitations of scale and time governing the research presented here render such a thorough evaluation difficult, if not impossible. Nevertheless, to *initially* validate its impact and to gather an understanding of its transferability and applicability to industrial practice, the DFμA methodology has been applied to selected areas of microassembly. Furthermore, it was discussed in detail in an organised workshop (see section 3.2.1), and meetings with industrial partners, and different stages of the research have been presented at a number of relevant conferences. This included major development work (Tietje and Ratchev, 2007, Tietje and Ratchev 2007a, Tietje and Ratchev 2007b), different aspects of the application and validation (Tietje *et al.*, 2008a, Turitto *et al.*, 2008, Ronaldo *et al.*, 2008), and future trends (Tietje *et al.*, 2008b). In addition, the work has been applied within a UK national research project. Although these efforts do not replace the thorough industrial examination mentioned above, it can reasonably be claimed that obvious flaws would have been identified in the process of validation as conducted thus far. No major concerns have been raised yet, and any feedback offered has been considered in the process of developing the methodology.

The object of this chapter is to outline the efforts made towards verifying the proposed DFμA methodology, representing an initial indication of its validity. The research outcomes are illustrated through application to two microassembly scenarios of practical relevance in two key industrial areas in the UK, metrology and healthcare (see section 3.3.2 for detailed justification regarding the test case selection). The scenarios represent the DFμA process for the assembly of:

- A micro-/nano measurement device
- A three-dimensional minifluidics device for blood analyses

The test cases embody and probe selected aspects behind the research carried out, while illustrating and further exploring the possibilities of its application. The scenarios are described with reference to the DFμA methodology. The chapter illustrates core components such as the assembly capability model (Chapter 4) and a selection of DFμA guidelines (Chapter 6) within the overall DFμA methodology (Chapter 5).

The first steps toward a software implementation of the methodology are illustrated through graphical user interface (GUI) screenshots within section 7.1. This is followed by describing the verification through the actual test cases in sections 7.2 and 7.3. The product requirements and microassembly difficulties are clearly defined, clarifying their relevance to the DFμA verification. The methodology is applied and illustrated, and the outcomes are described, these including the implementations of the respective assembly systems. Finally section 7.4 summarises and discusses the verification results.

7.1 Towards an initial software implementation

An initial software system has been started to illustrate elements of the DFμA methodology. The frontend environment has been created using *Visual basic express 8*, based on the *Microsoft.NET framework*, which is procedural and fully object-oriented.[15]

Figure 62 gives a schematic overview of the envisaged software environment. The program is Windows application-based and the following main functions can be accessed through a graphical user interface:

- *Decision support for microproduct design*

  This starts a range of application forms assessing the complexity of a current design. Furthermore, it enables the selection of microassembly processes. Finally, support is given in optimising the microproduct parts with reference to the candidate assembly processes identified.

- *Updating of DFμA guidelines*

  Experienced design engineers get the opportunity to store their know-how in appropriate checklists.

- *Microassembly process characterisation*

  This is an important aspect of the environment because it is here that the characteristics and capabilities of microassembly processes are captured.

- *Product and part domain*

  In this domain the product requirements are captured. In the course of the product development from conceptual to embodiment design ever more details of the product components and its properties are obtained.

- *Micorassembly process domain*

  The microassembly process domain knowledge is needed to enable the

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[15] The fundamental idea of *Object oriented programming* (OOP) is to combine and encapsulate data (and functions applied to these data) into so called *objects* allowing for flexibility and reuse.

process sheets (see section Figure 39). It is the basis for supporting process selection, and thereby the optimisation of the product components (through communication with *the product and part domain*).

- *DFμA guidelines*

  General product-related guidelines are stated here. Specific milieu- and process-related guidelines are accessible via checklists. Guidelines can be updated by the skilled designer and experiences can be derived from previous DFμA projects.

In addition, a tool for documentation of previous DFμA projects is an important aspect because it enables the storage of r*eference cases*, providing the facility to identify by 'family resemblances' possible problems and so pre-empt their occurrence. This introduces the possibility of bringing c*ase-based reasoning approaches* into the environment.

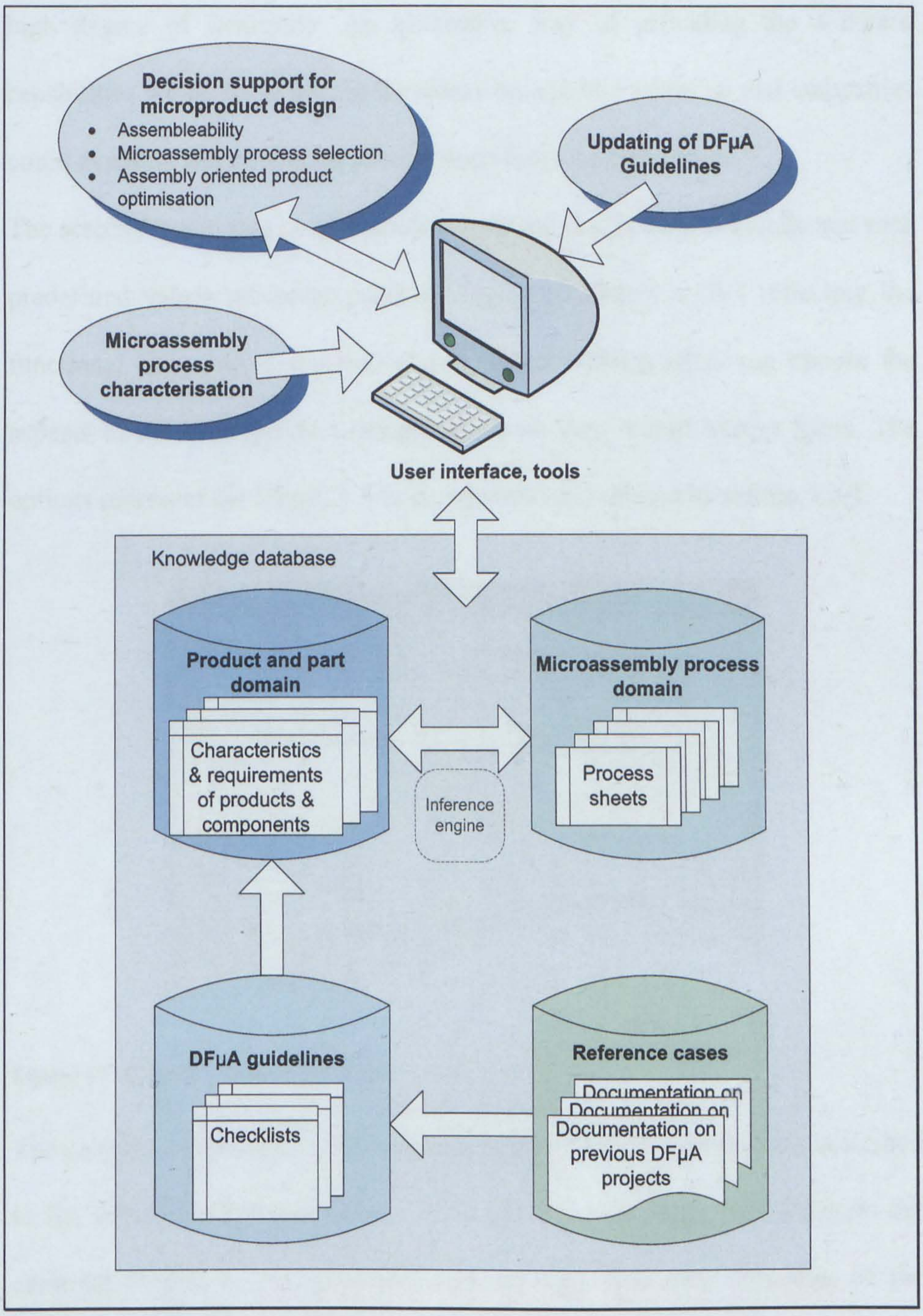

Figure 62: Overview of initial software environment

It should be possible to implement a software package locally within an individual business, updating the database with its existing available process pool while ensuring confidentiality. This is especially useful when the budget to invest in new equipment is low or existing equipment is characterised by a high degree of flexibility. An alternative way of providing the software capabilities would be to run the databases on a public server so that companies could examine and download process knowledge as appropriate.[16]

The screenshots in this chapter show a frontend that is easy to handle and uses predefined values wherever possible. Figure 63 shows a GUI reflecting the functional perspectives outlined above. When starting, users can choose the aspects of the microproduct design on which they would like to focus. The options represent the DFμA's core components as outlined in section 5.2.3.

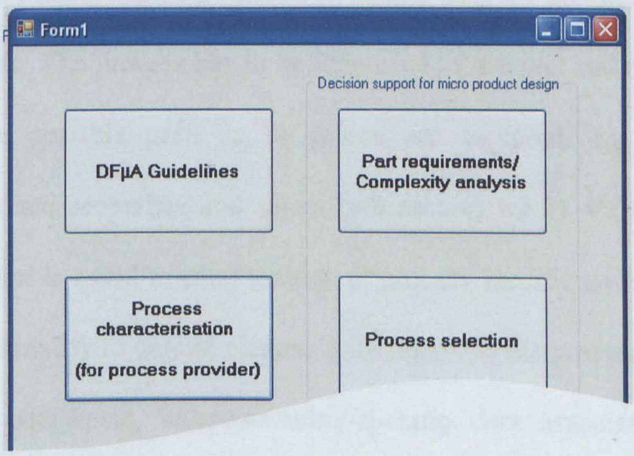

Figure 63: Optional system functions

The process selection and the process characterisation frontend are described in the following two subsections 7.1.1 and 7.1.2, because they illustrate the essential aspects of the developed methodology. The main functions of the initial implementation will also be outlined.

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[16] It has to be made clear at this point that the work did not focus on building an *inference engine* to automate the reasoning process yet. Nevertheless, commercial or open source inference engines are readily available (e.g. jess, clips, IQ-engine etc.). The work carried out here can be seen as fundamental, enabling the introduction of such an inference engine and its rule base in the future.

7.1.1 Process characterisation frontend

The process characterisation function is necessary to enable the process provider to supply necessary information on its processes and equipment. The process provider is guided through the Windows application and the relevant forms that need to be processed to derive the process knowledge that provides a foundation for assembly-oriented design and process selection. The provider has to select what kind of processes can be provided, according to the main classes, joining, feeding, and handling. A template containing structured questions is provided. Figure 64 shows an example for the characterisation of a joining process. The process has to be identified by a name and the properties regarding the possible parts to be joined are captured, e.g. processable materials, surface properties and so on (see section 4.4.3). Furthermore, the process supplier is asked to enter a range of process-specific guidelines. There is also the possibility to upload pictures with regard to the process's functional principle or equipment. Microassembly-specific data associated with the implementable joint is captured. The joint accuracy, minimal joint size, and joining surface area, as well as the integration of functions into the joint, are covered here. For further decision-making it is important to analyse economic criteria, hence data such as equipment cost (fixed cost), processing/operating cost (variable cost), and cycle time are captured in a separate form.

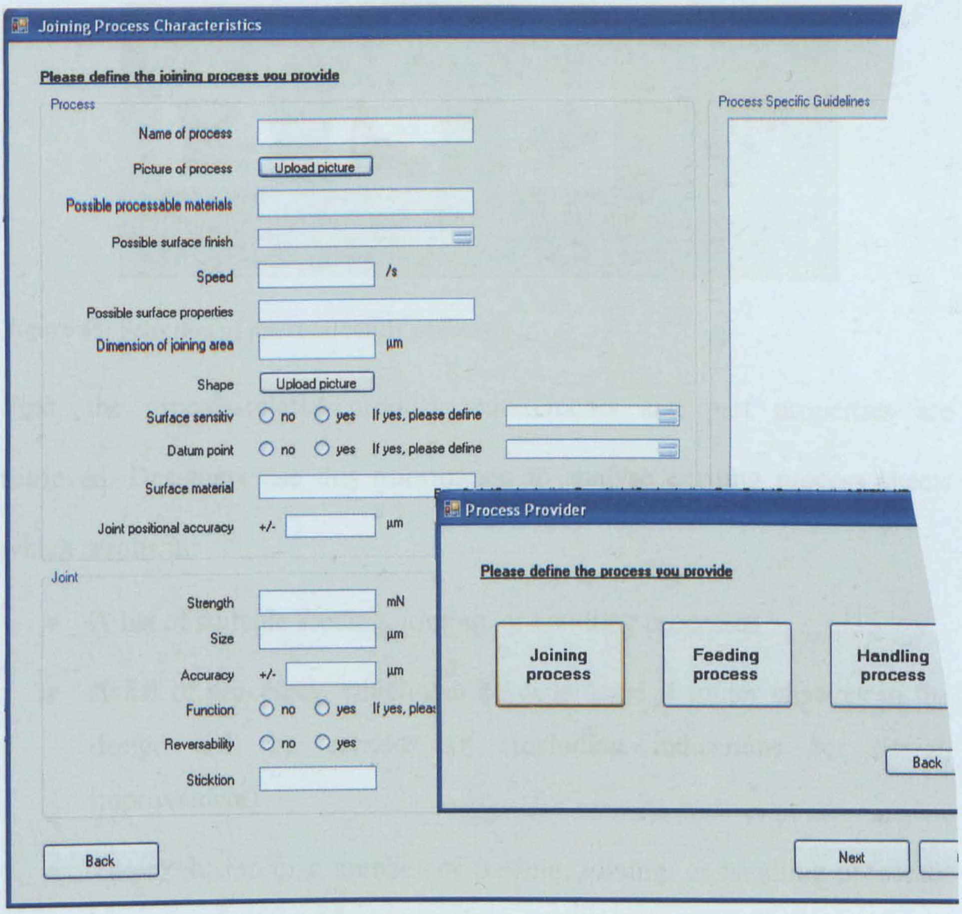


Figure 64: Joining process characterisation

The captured data is used to gain knowledge in the corresponding domains, providing process domain knowledge, DFµA guidelines, and a basis for a rule-based system (e.g. the use of an inference engine) to automate the process selection procedure.

7.1.2 Process selection interface

The process selection environment includes choosing feeding, handling, and joining processes (see Figure 65). By default, the selection order would be feeding, joining, handling. In this way subassemblies are considered in the selection of handling processes.

Figure 65: Selection of microassembly processes

First, the process-related product requirements and part properties are retrieved. Designers use this information to analyse existing process sheets which results in:

- A list of suitable feeding, joining, or handling processes
- A list of processes, which can be considered if minor changes in the design will be carried out (including indications for design improvement)
- The exclusion of a number of feeding, joining, or handling processes because of major design problems and/or incompatibility with the process-related product requirements

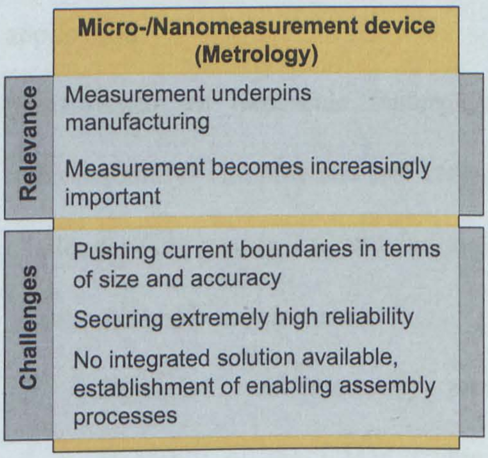
To decide between several suitable processes, economic data can be assessed to inform the decision-making. The following sections 7.2 and 7.3 deal with the practical test cases which represent substantial industrial relevance and so provide further insight into the DFμA application.

7.2 Test case 1 – Micro-/Nanomeasurement device

The first test case is an assembly problem provided by the National Physical Laboratory (NPL).[17] It concerns the design and assembly of a micro-/nano

[17] NPL is *"a world-leading centre of excellence in developing and applying the most accurate measurement standards, science and technology available to man"* NPL (2008) About NPL. http://www.npl.co.uk, National Physical Laboratory.

measurement device. The problem encompasses a number of demanding design and microassembly issues (see section 7.2.1) and for this reason can be understood as precisely the kind of test that will rigorously examine the usefulness of the DFμA approach. The assembling of a state-of-the-art *CMM stylus* addresses a critical need in micromanufacturing by its ensuring accuracy and consistency in the measuring of increasingly miniaturised microparts. The strategic importance of this test case has been described in section 3.3.2. The textbox below provides the detail of the test case, summarising its generic purpose, general relevance, and associated challenges.



Selection of DFμA test case 1

A push in metrology equipment is required to respond to the ongoing trend of miniaturisation. The satisfying of the requirement will enable quality assurance for arising three-dimensional products with nanometre scale features.

The assembly problem is provided by the National Physics Laboratory. The objective is to enable assembly of a state-of-the-art CMM stylus, a task which is characterised by extremely rigid and challenging requirements.

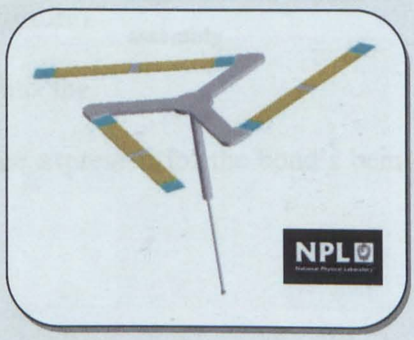


Figure 66: Test case 1 – micro-/nano-CMM probe

The following subsection 7.2.1 describes the specific verification significance of the use case. The critical issues of the probe assembly are defined, clearly identifying the microassembly problems.

7.2.1 Requirements and problem formulation

The object of this section is to give a clear explanation of product requirements and the presented task. The definition of requirements and the identification of microassembly problems that have to be addressed serve as a frame of reference for the eliciting of the verification results. It can be seen as the foundation or precondition to describing the outcome of the methodological application.

Measurement of nanoscale features imposes demanding requirements on microassembly. The practical test case reflects a range of microworld-inherent challenges (see section 2.4) and demanding requirements set by NPL, such as:

- *Assembly requirements*

  Figure 67 schematically represents the assembly of the CMM stylus. To assure functioning of the product, it is critical to maintain a 90° angle between plate (flexure) and pin. No introduction of stress into the parts is allowed. There is a preference expressed for the bond's being made reversible.

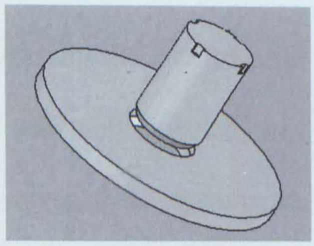


Figure 67: Pin in plate assembly

- *Tight tolerances*

  The measurement purpose of the product requires tight tolerances to assure in practice the predicted and simulated behaviour of the probe. NPL wants that the stylus should be fixed to the centre of the carrier plate (flexure) *"as accurately as possible"*.

- *Sticking effects*

  Due to the small size/dimensions of the stylus, sticking effects can occur (Figure 68 shows the stylus in perspective to a 20 pence coin).

Figure 68: CMM stylus in perspective

- *Fragility and sensitivity*

  Functional elements of the product are sensitive to contamination and vibration.

- *No integrated solution currently possible*

  The product represents the targeted area of this research, which cannot be carried out without microassembly. The product represents an *enabling technology* that pushes the boundaries of the current the state-of-the-art.

- *Functional requirements on conceptual designs*

  A combination of strict functional requirements and the lack of prior experience in designing the product in an assembly-oriented way impose limitations on freedom of design. However, there remains the possibility to adapt the design as required for assembly orientation. That is, the conceptual design stage is the appropriate starting point for the applying of the DFμA methodology.

Although the envisaged production volume of this product is very low (according to NPL's specification: max. 10 units/d) the test case was selected because of its extremely demanding challenges in terms of microassembly requirements, challenges which render manual assembly impossible. In addition, the product consists of just two parts: the application of the methodology is focussed in part on the questions of how to assemble these, but more particularly on how they can be optimised to enable assembly according to the requirements outlined.

The starting point from the DFμA perspective is the initial design as provided by NPL. The conceptual design was decided on and Finite Element Model (FEM) -based vibration analyses were carried out to optimise the function. At that point, initially manufactured parts were provided for assembly. These were used as a learning case for the DFμA methodology. Figure 69 shows different product design stages including the process of capturing requirements and the characteristics of a stylus component.

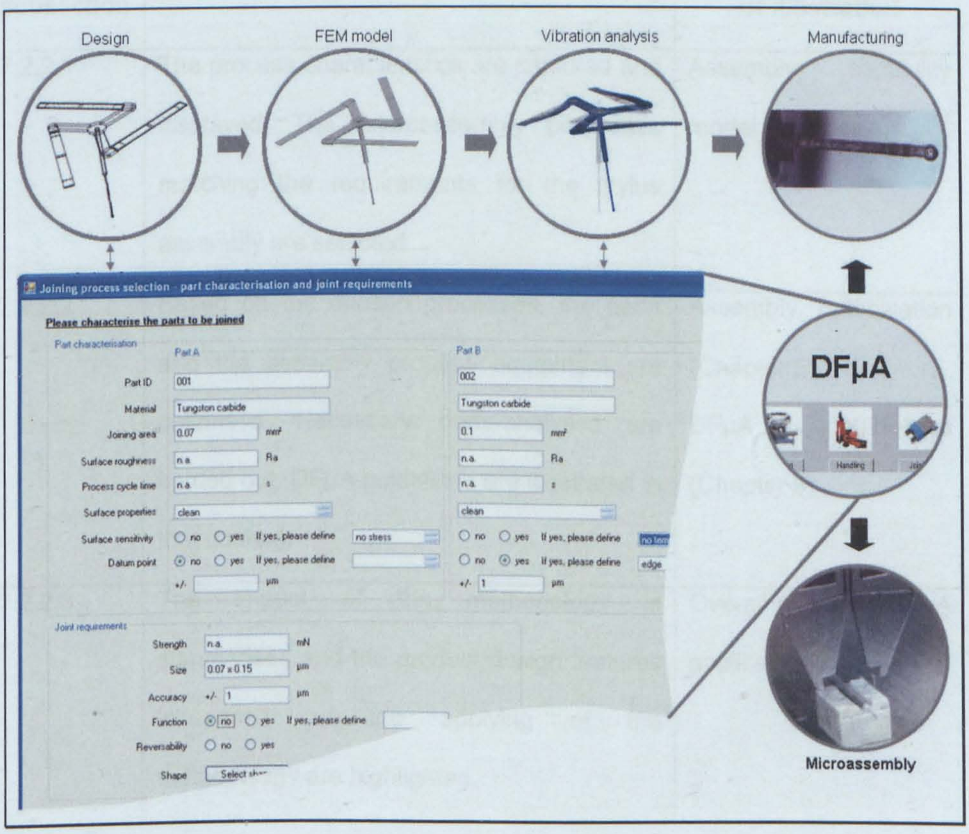


Figure 69: CMM stylus development process

7.2.2 Application of DFμA methodology

The structured approach suggested by the DFμA methodology and applied to the CMM stylus assembly is illustrated in this section.[18] The results are underpinned by showing the implemented microassembly system (see section 7.2.3).

The following table summarises how applying the DFμA to the test case provides verification and illustration. The key points are explained and the elements of the DFμA methodology put to the test are described.

Table 7: Illustration and verification via application of DFμA methodology – test case 1

Respective subsection	Synopsis	Subject to verification or illustration
7.2.2.1	The process characteristics are captured and displayed. The microassembly processes matching the requirements for the stylus assembly are selected.	Assembly capability model (Chapter 4)
7.2.2.2	Based on the chosen processes, the parts and the assembly process equipment are optimised. Necessary parts-analyses are carried out. DFμA guidelines are illustrated in that context.	Assembly optimisation (Chapter 5) DFμA guidelines (Chapter 6)
7.2.2.3	The impact of the methodology is summarised and the product design features influenced by the applying of the methodology are highlighted.	Overall results of DFμA application

The chosen product consists of two parts, which are characterised by high

[18] The DFμA methodology has been applied to the test case provided by NPL. The *author* has for that purpose visited NPL in London and received NPL experts in Nottingham.

functionality. In terms of complexity and functionality the product is well designed.

7.2.2.1 Process selection

The assembly processes and equipment have been selected based on the product requirements and part characteristics. Table 8 shows the capabilities of the chosen assembly processes (process sheets), full details are provided in Appendix E.

Table 8: Linear stages – key characteristics

	Linear stage – Klocke Nanotechnik	**Part design influences**	**System design influences**
Resolution	2nm	Accuracy, self-alignment features,	Passive alignment
Repeatability	<10nm	Accuracy, self-alignment features, passive alignment	Vibration, controlled environment
Workspace (Stroke, reach)	50mm	Dimensions, product structure	Integration of axis
DOF	1	Product structure, layout	Integration of axis
Payload	2kg	Material, geometry (mass)	
Speed (max)	5mm/s		Cycle time
Operational restrictions	horizontal operation		System integration
Equipment dimensions Length (stroke direction) Width (max) Height	 80mm 34mm 13mm		System dimensions, integration, desktop factory
Modularity (control, accessories)	Combination with other stages possible. horizontal operation		System integration
Vacuum compatibility	yes		Resulting from part requirements

The processes were chosen based on the need to match part- and microassembly process-characteristics. In particular, the requirements for high accuracy and the stress-free joint led to the selection of linear stages with accuracies in the range of nanometres and the choosing of adhesive bonding as the joining process. The piezo-based linear stages represent current state-of-the-art, providing positioning repeatability of 10 nanometres through closed-loop control. These were chosen to allow the required precise alignment of the stylus to the centre of the plate/flexure (see section 7.2.1).

7.2.2.2 Optimisation with regard to microassembly

The parts are characterised in more detail in order to allow for their being adapted with reference to the processes. The DFμA methodology was used to influence the stylus design. The aim is to facilitate easier assembly and assure perpendicularity. The principle of passive alignment is used to guarantee the correct orientation of the part within the selected gripper so that the part is inserted at (or at a very near approximation of) the 90° angle required. In order to satisfy this requirement, different possibilities were tested to adapt the existing gripper to the part design. Figure 70 shows the handle that was designed to fix the position of the stylus while composing it to the fixed flexure and waiting until the adhesive cures. By this means, sticking effects between gripper and stylus are avoided. The sticking effects that occur between the stylus and its handle are helpful because they keep the stylus within the V-groove. The handle allows controlled part-grasping from the sides, due to the sides' being parallel (this proven by SEM). Furthermore it allows the applying of grasping force without damaging the part (see Figure 71).

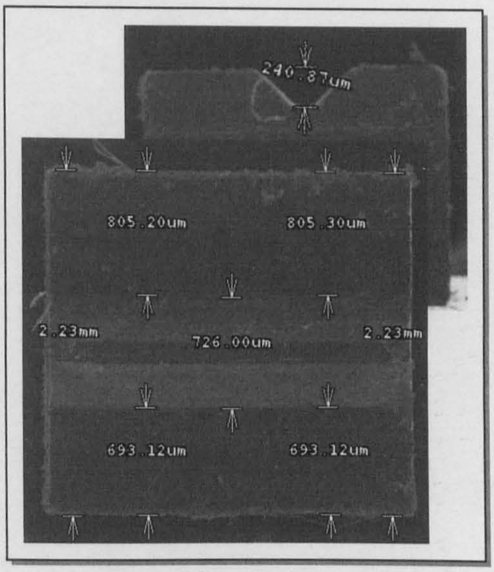


Figure 70: Gripping handle

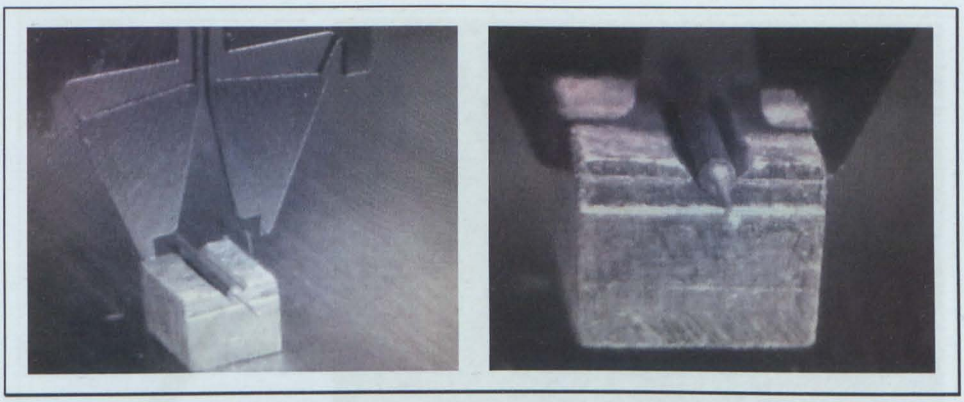


Figure 71: Passive alignment handle for gripping the stylus

Adhesive bonding was chosen to realise the joint between stylus and flexure. The way in which the stylus provided has been manufactured leaves it with a very characteristic feature on the non-functional end. This end has been carefully analysed in order to determine how best to optimise the joint for adhesive bonding (see Figure 72).

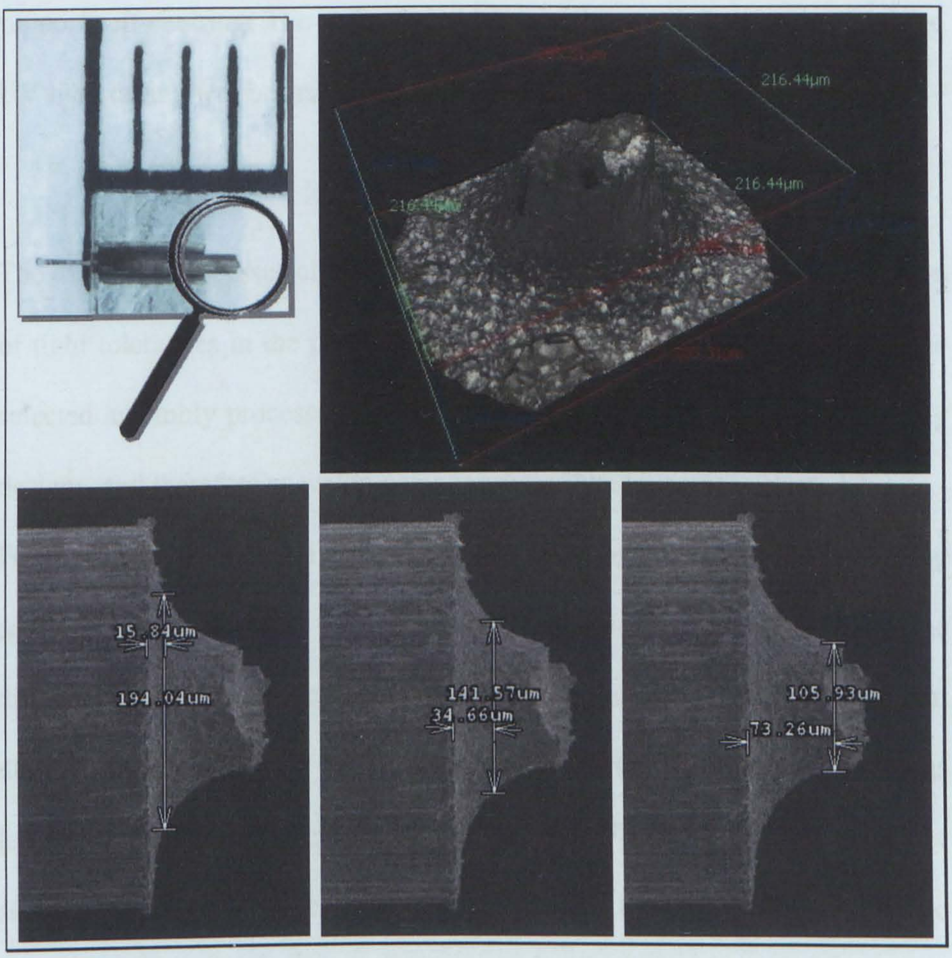


Figure 72: Characterisation of joining surface

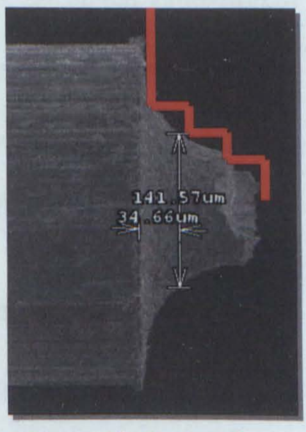


Figure 73: Probe joint design

The feature can be understood as providing an ideal circumstance in which to exploit the capillary effects which ordinarily *disturb* the microassembly process. For the purpose of the coupling, the probe end is seen as positive and the flexure as negative. The flexure has to be designed in the way indicated by the red line in Figure 73, following the form of the stylus. The glue will be dispensed onto the flexure and through capillary forces distribute evenly around the hole. When the probe is inserted it will be attached to the flexure and both the shape and the glue will support self-centring. The stylus is held in position until the glue is cured (no UV light curing will be employed, so as to avoid the introduction of stress).

7.2.2.3 Impact of the methodology

The assembly processes chosen are considered in the design. The combination of tight tolerances in the part's design together with the characteristics of the selected assembly processes allow for the required accuracy. Other assembly designs, and therefore as well assembly process chains, were evaluated.

For this test case, the main impact of the methodology is related to the gripping process (encapsulation of the stylus) and the joint design (capillaries for glue dispensing and chamfer for insertion and self-alignment). It can be stated that the preliminary results of the outlined validation are promising. The lessons learned go into the further development of the DFμA tool. The methodology still relies on human reasoning and interaction but can be understood to provide support both to the design process and the selecting of microassembly processes. Future work can be divided into two strands: the actual validation of the probe assembly needs to be carried out, and the assembled probe needs to be integrated into a metrology system. The assembly system layout that was designed and set up is described and illustrated in the following section.

7.2.3 Implementation of microassembly system

The implementation of a microassembly system, comprising both the hardware setup and the relevant validation routes, is described in this subsection. The system is used to affix the stylus to the plate and is characterised by three DOF realised by three linear piezo-driven stages (X, Y, and Z). A camera is used to observe the process. A piezo-driven gripper, attached in Z-direction to a force sensor is used to steer the pin into the plate. A glue dispenser is used to bond the parts together.

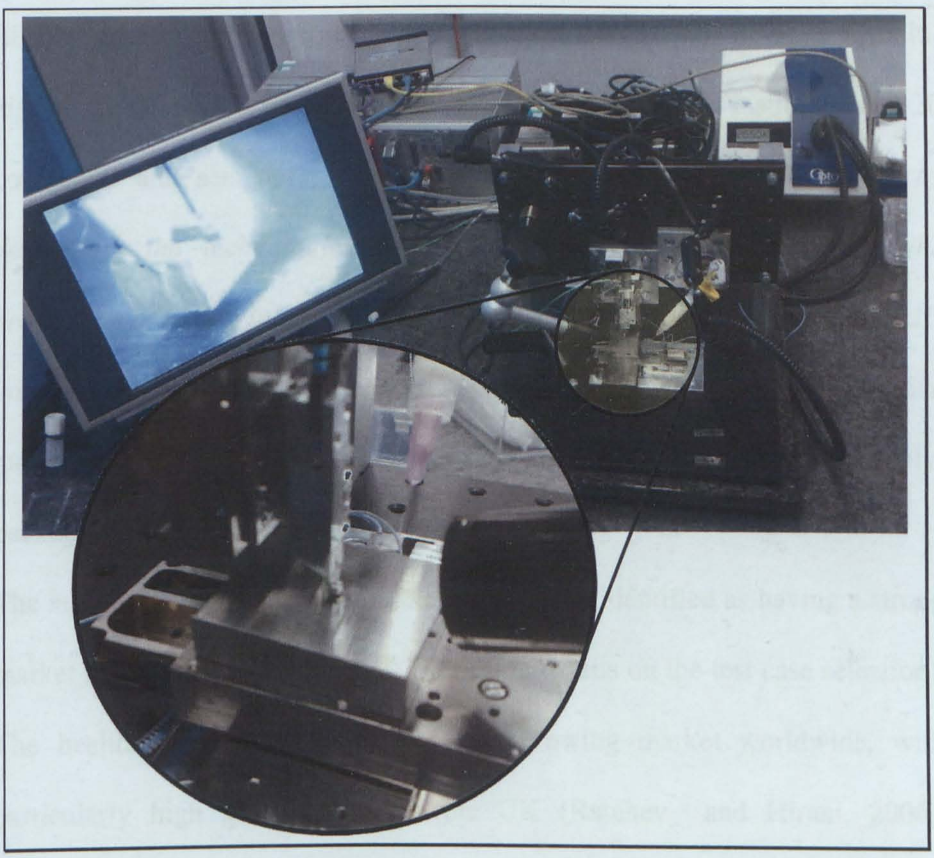


Figure 74: Microassembly implementation for microprobe test case

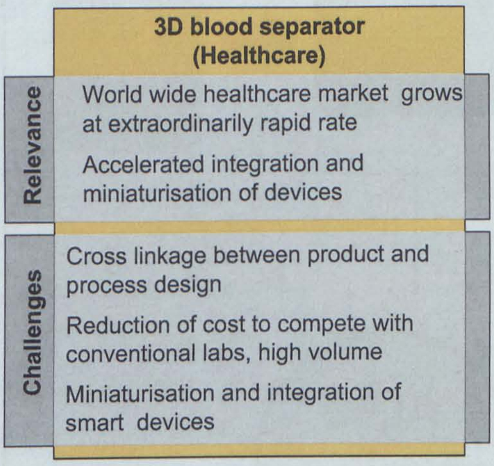
Figure 74 gives an overview of the whole system, including a network controller and light sources as well as a detailed view of the tool centre point. The figure displays the linear stages as well as the gripper (together with force sensor attached to linear stage in Z direction), the camera, and the glue dispenser. Detailed descriptions of the system elements can be found in Appendix E.

The chosen system setup allows inspection and supervision of the assembly process. High quality is assured here by the fact that information regarding the geometry, force, pressure, and surface roughness of the parts, as well as the adhesive properties, is available when joining the parts.

7.3 Test case 2 – Minifluidics device

The second test case presents a demonstrator product developed within the UK EPSRC grand challenge project *3D Mintegration* (3DM). 3DM is a multi-disciplinary research programme involving eight research institutes and 20 companies and sets out to create *"a paradigm shift in manufacturing by developing the technologies and strategic approaches required for the production of highly-integrated, cost-effective and reliable multi-functional 3D miniaturised/integrated devices"* (3D-Mintegration, 2007). It aims to provide radically new ways of thinking for end-to-end design, processing, assembly, packaging, integration, and testing.

The *minifluidic blood separation device* has been identified as having a strong market relevance (see section 3.3.2 for more details on the test case selection). The healthcare sector represents a fast growing market worldwide, with particularly high growth rates in the UK (Ratchev and Hirani, 2006). Accordingly, one of the main challenges is the establishment of cost-effectiveness, which imposes additional restrictions on the assembly process. Increasing sophistication of medical devices in terms of performance is accompanied by higher complexity of the devices' components, such that joining is one of the key processes in the manufacture of medical devices. Because of this consideration, the joining process has been singled out as critical, imposing strict requirements (see section 7.3.1). What has further informed the selecting of specific aspects of the second test case is that doing so allows for a focussing on features not addressed in looking at the stylus assembly case, and so for a further demonstrating of the scope of the DFμA methodology. The textbox below outlines briefly the generic purpose, general relevance, and challenges of the second test case.



High market relevance has been identified for the *minifluidic blood separation device*. The healthcare sector represents a fast growing market worldwide, with particularly high growth rates in the UK.

The test case is subject to research within the *3D-Mintegration* project. A three-dimensional minifluidics device is envisaged to enable blood-plasma separation, in preparation for further biological analyses and diagnostics.

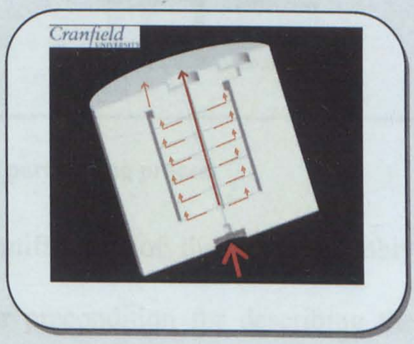


Figure 75: Test case 2 – 3D Blood separator

7.3.1 Problem definition and joint requirements specification

As explained above, the selection and optimisation of the joining process has been singled out. This section highlights the joining problem by describing the task to be completed. Figure 76 shows the development process from the initial design idea to the assembled device. A three-dimensional product has been conceptually designed within the 3DM consortium and an embodiment design and prototype parts have been provided to the University of Nottingham by Cranfield University.

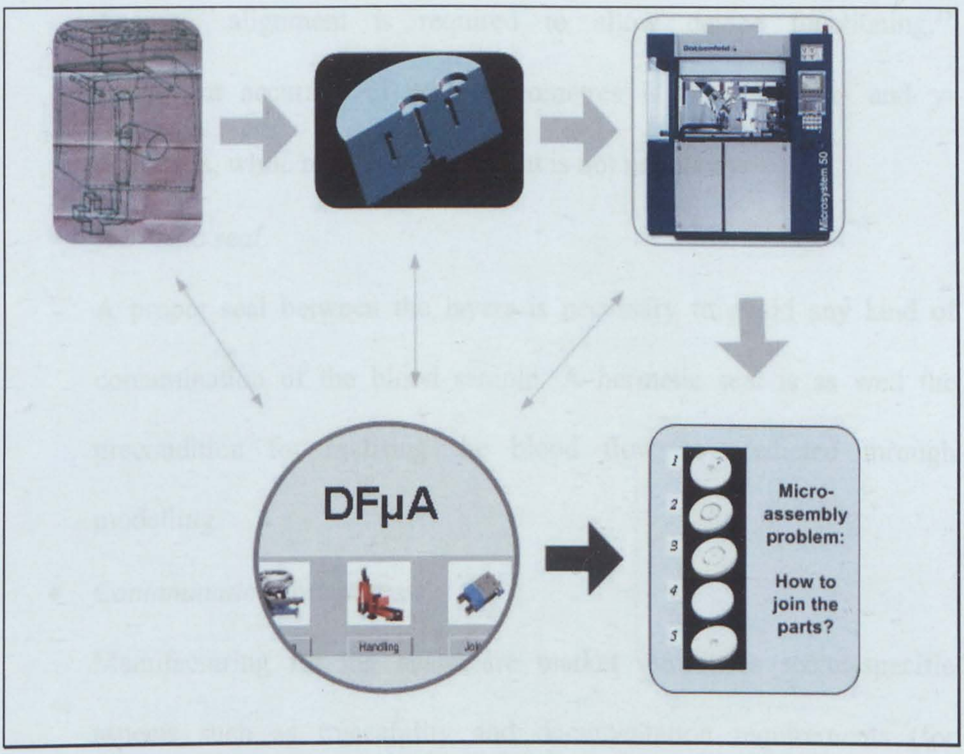


Figure 76: Application of DFμA to the minifluidics part joining process

The defining of requirements and the identification of the microassembly problems can be seen as the foundation or precondition for describing the outcome of the methodological application. The requirements with regard to the joining mechanism can be summarised as follows:

- *Assembly process*

  Five or more discs need to be joined on top of each other (in a stack). The parts need to be held in position during the joining process. Perpendicularity of features to the first surface has to be maintained.

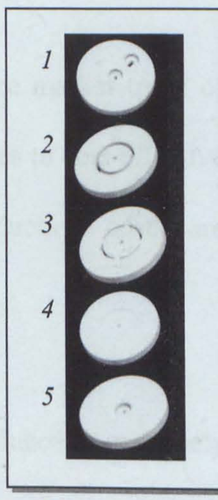


Figure 77: Part assembly – minifludics device

- *Accuracy of joint and placement*

  The dimensions of the channels are calculated to enable blood flow and plasma separation.

Accurate alignment is required to allow device functioning.[19] Alignment accuracy of ±20 micrometres is desired in x- and y-directions, while rotational alignment is not necessary.

- *Hermetic seal*

  A proper seal between the layers is necessary to avoid any kind of contamination of the blood sample. A hermetic seal is as well the precondition for realising the blood flow as predicted through modelling.

- *Contamination-free process*

  Manufacturing for the healthcare market introduces sector-specific aspects such as traceability and documentation requirements (for example, as necessary for FDA approval). Two further conditions obtain here. First, *it is necessary to avoid contamination.* Second, *nothing can be done that might affect the parts' biocompatibility.* All this is of course in addition to assuring the proper functioning of the product in accordance with good manufacturing practices (GMP).

- *Low cost*

  As outlined above, the product targets the healthcare market trend of moving from analysis in expensive central laboratories to cost-effective point-of-care diagnostics. Accordingly, low production costs are essential in order to be competitive.

- *High volumes*

  The item is disposable and therefore needs to be produced in extremely

[19] Functioning is based on the flow behaviour of blood. The design is based on calculations and simulations carried out at the Universities Heriot-Watt, Greenwich, and Cambridge.

high volumes, creating a need for very short cycle times.

The aspect of cost efficiency was seen as very important to show that the methodology can have an impact on the mass market or when upscaling production. This actually addresses and underpins the overall intention of this research, transferring prototypes to industrial practice.

7.3.2 Application of DFμA methodology

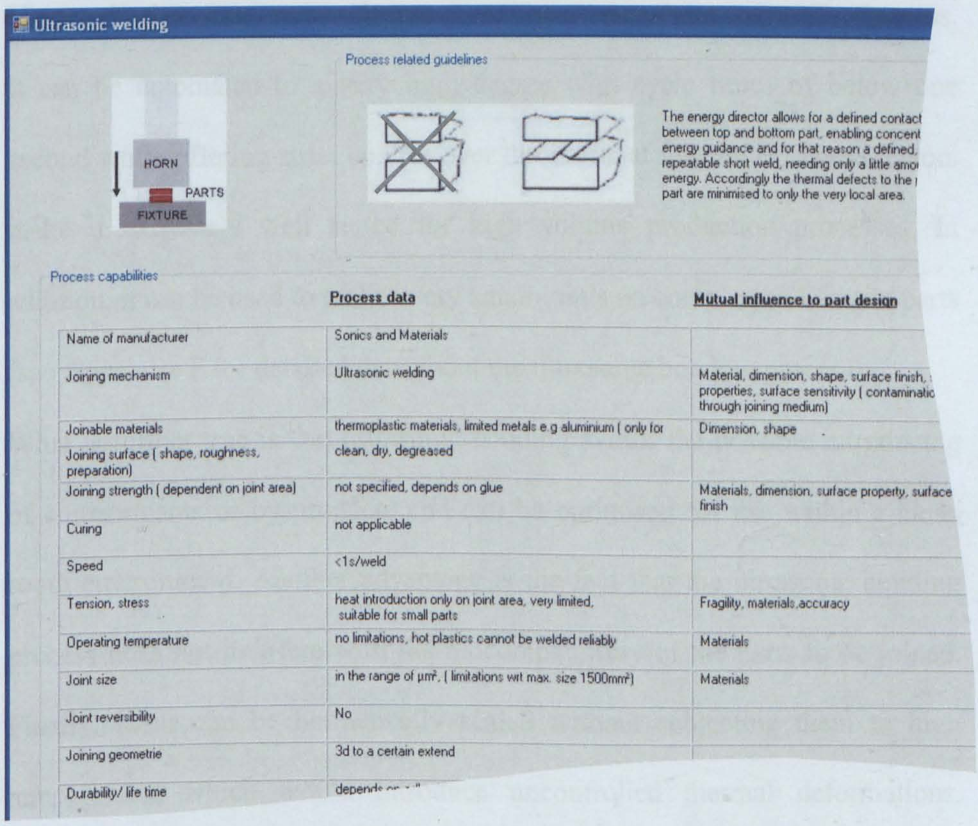
This section describes the application of the DFμA methodology to the task of joining parts for the microfluidic device. The following table summarises the key points addressed and describes the elements of the DFμA methodology that are tested.

Table 9: Illustration and verification of DFμA methodology application – test case 2

Respective subsection	Synopsis	Subject to verification or illustration
7.3.2.1	The process characteristics are displayed. The reasons for choosing ultrasonic bonding are explained.	Assembly capability model (Chapter 4)
7.3.2.2	Based on the ultrasonic bonding process, the part joining areas are optimised. The necessary analyses are carried out. The application of process-specific guidelines is illustrated in that context. The design features influenced are highlighted, proving the impact of the methodology.	Product-assembly optimisation (Chapter 5) DFμA guidelines (Chapter 6)

7.3.2.1 Process selection

This section shows the characteristics of the ultrasonic joining process and explains why it was chosen for the assembly task to be tackled here. The joining process implemented, including the assembly-oriented optimisation of the product, is shown in section 7.3.3. The assembly processes and equipment have been selected based on the defined requirements and the parts characteristics. Figure 78 shows the capabilities of the chosen ultrasonic bonding processes.



	Process data	Mutual influence to part design
Name of manufacturer	Sonics and Materials	
Joining mechanism	Ultrasonic welding	Material, dimension, shape, surface finish, properties, surface sensitivity (contaminatio through joining medium)
Joinable materials	thermoplastic materials, limited metals e.g aluminium (only for	Dimension, shape
Joining surface (shape, roughness, preparation)	clean, dry, degreased	
Joining strength (dependent on joint area)	not specified, depends on glue	Materials, dimension, surface property, surface finish
Curing	not applicable	
Speed	<1s/weld	
Tension, stress	heat introduction only on joint area, very limited, suitable for small parts	Fragility, materials,accuracy
Operating temperature	no limitations, hot plastics cannot be welded reliably	Materials
Joint size	in the range of µm², (limitations wrt max. size 1500mm²)	Materials
Joint reversibility	No	
Joining geometrie	3d to a certain extend	
Durability/ life time	depends on ...	

Figure 78: Process sheet – Ultrasonic bonding (screenshot of the software prototype)

The process selection is based on factors and requirements described in section 7.3.1. An ultrasonic bonding mechanism is chosen because it addresses all requirements outlined (see Figure 79). Explanation regarding the reasoning behind the selecting of ultrasonic bonding is provided below.

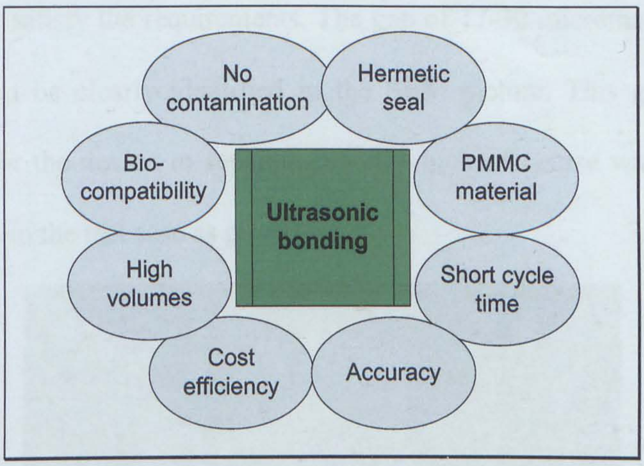


Figure 79: Requirements-based selection of ultrasonic bonding

Ultrasonic bonding was selected here because of its cost-effectiveness. It can be automated to a very high degree with cycle times of below one second while offering strict control over dimensional tolerances. These factors make it extremely well suited for high volume production processes. In addition, it can be used to realise very small joints on complex and fragile parts (see Appendix F for detailed data about the ultrasonic bonding process).

What is further true is that ultrasonic bonding avoids the possible introducing of contaminants or by-products and can be optimised for use within a clean room environment. Another advantage is the fact that the ultrasonic bonding process does not interfere with the biocompatibility of the parts to be joined. Finally, items can be hermetically sealed without subjecting them to high temperatures which would introduce uncontrolled thermal deformations. Ultrasonic bonding can be seen, then, as an ideal approach for manufacturing applications within the medical sector.

7.3.2.2 Optimisation of parts and joining process

The first assembly was carried out on parts as delivered to the University of Nottingham. Figure 80 shows the results of these first trials, resulting in a seal that does not satisfy the requirements. The gap of 17-30 micrometres between two discs can be clearly identified in the SEM picture. This gap makes it impossible for the device to separate blood, which of course was one of the requirements in the test case as given.

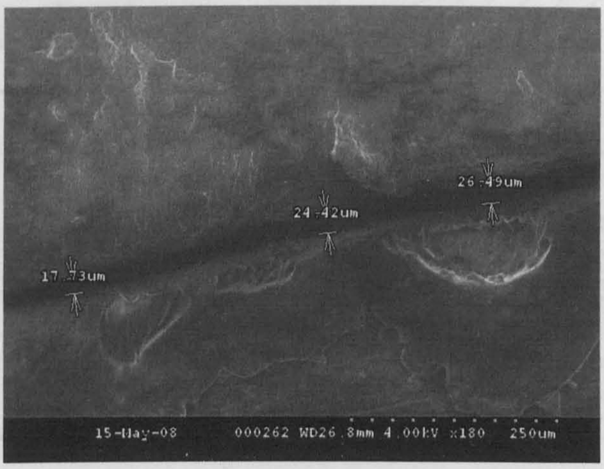


Figure 80: SEM analysis – no sealed joint

According to the DFμA method, the parts should be adapted to the chosen process. In this case the process sheet for ultrasonic welding provides guidelines for geometric joint optimisation (see Figure 78). To improve the results of the bonding process, an area specifically dedicated to realising the joint was introduced to the parts (see Figure 81). The energy director allows for a defined contact surface between the top and bottom parts, enabling concentrated energy guidance and so for a defined and repeatable short weld requiring only a small amount of energy. By this means, the thermal defects occasioned to the plastic part are minimised, contained to only a very local area.

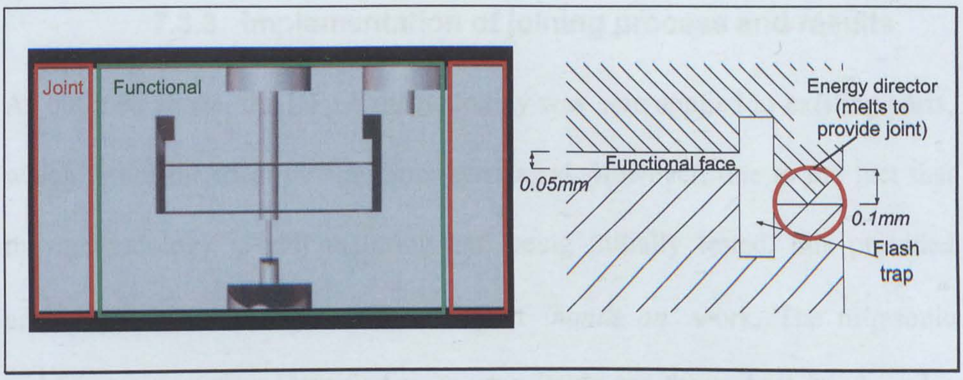


Figure 81: Design adaptation for ultrasonic welding

In addition, it was identified that the surface roughness needs to be reduced to enable better contact between the joining surfaces. To test the redesign, the moulded parts were modified on a high precision machining centre.[20] Figure 82 shows the design of the part modification and the 3D picture including the surface roughness. The figure also shows the improvements made to the surface by polishing with the machining centre.

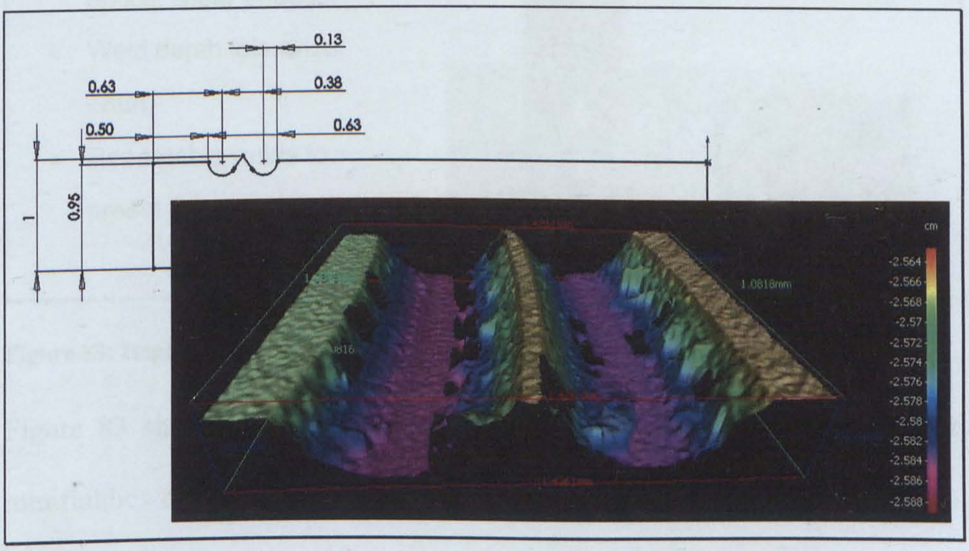


Figure 82: Part modification – energy director

[20] KERN Evo, precision on the workpiece ±2.0 µm - KERN (2008) KERN Evo - Ultra precision CNC machining centre. http://www.kern-microtechnic.com/oldpage/PDFs/KERN-EVO-e.pdf Kern Micro- und Feinwerktechnik.

7.3.3 Implementation of joining process and results

As outlined above, the DFµA methodology was here applied to existing parts, which is not the ideal circumstance envisaged. However, due to the fact that the methodology is still maturing and being initially tested, this provided advantages by allowing for the doing of *'hands on'* work. The ultrasonic welding process was identified as most suitable for the task at hand, and a process sheet for ultrasonic welding was filed. This provided valuable insight into the process of guiding the product designer in adapting the product design and optimising it towards the selected microassembly (here, joining) process.

Ultrasonic welding equipment:

- *"Sonics and Materials"*
- Stepper motor drive with optical linear encoder
- Weld depth tolerance: ±8µm
- Repeatable welds to preset final requirements

Figure 83: Implemented ultrasonic welding equipment

Figure 83 shows the system that was used to assemble the discs for the minifluidics device. The product requirements are translated into the system necessities that are identified as critical and need to be examined. The impact of surface roughness was analysed, and high alignment accuracy was realised through a fixture produced to hold the disks in the exact position required.

Figure 84 shows the assembled parts and examines the bonding results of the changed part design under the SEM. An improvement on the initial result is clearly visible (compare to Figure 80).

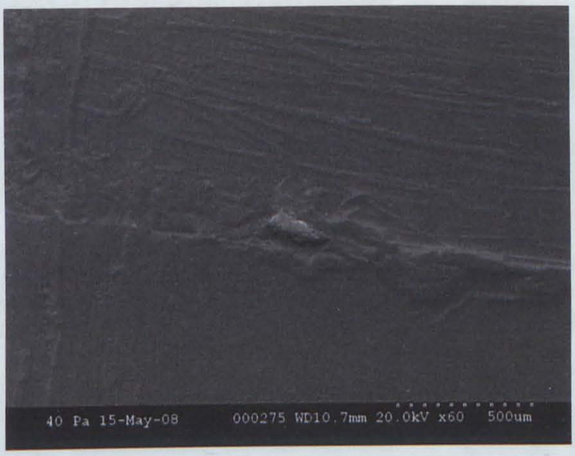


Figure 84: Assembled minifluidics device – hermetically sealed joint

The procedure in designing the minifluidics test case has been described in section 7.3.2. Figure 85 clearly illustrates the improvements and savings in time and cost that can be achieved through applying the DFμA methodology in the early design stages. The left-hand column shows the conventional design approach that was taken. As described above it resulted in parts that were unusable, due to an unsatisfactory joining process, and needed reworking to fulfil the requirements of the test case. Based on that reworking, the embodiment design was changed, which resulted in the need for new micromoulds for the microinjection process. These steps, which are time-consuming and costly, are highlighted in red. The right–hand column shows the process from design to production of the minifluidics device as performed guided by the application of the DFμA methodology early in the design stage, highlighted in green. The considering of process capabilities and related guidelines early in the design stage (see Figure 78 and Figure 79) led to a directly optimised product design.

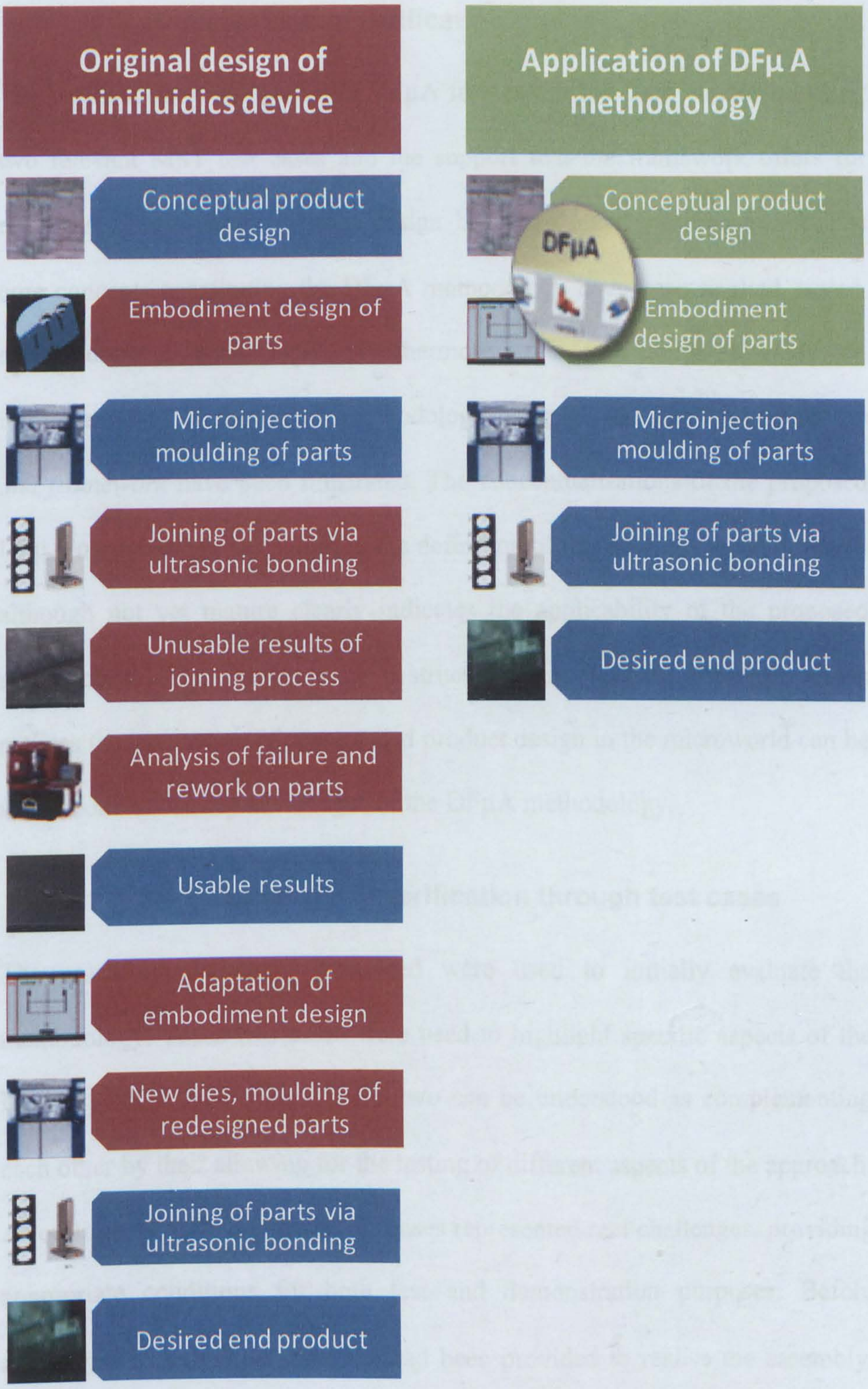


Figure 85: Benefits of applying the DFμA methodology to the design of the minifluidics device

7.4 Conclusions of verification

The verification of the proposed DFµA framework has been conducted using two relevant MST test cases and the support that the framework offers for microassembly-oriented product design has been clearly demonstrated. The core concepts constituting the DFµA methodology have been applied, tested, and illustrated accordingly. Furthermore, the first steps towards an implementation of the DFµA methodology using *Visual Basic* based on the *.net framework* have been illustrated. The conceptualisations of the proposed DFµA methodology were used in the definition of this software system, which although not yet mature clearly indicates the applicability of the proposed methodology. The provision of a structured and holistic approach which realises the integration of process and product design in the microworld can be seen as one of the key advantages of the DFµA methodology.

7.4.1 Summary of verification through test cases

The assembly challenges presented were used to initially evaluate the methodology. These two cases were used to highlight specific aspects of the DFµA methodology, such that the two can be understood as complementing each other by their allowing for the testing of different aspects of the approach. As outlined in section 2.4, the test cases represented real challenges, providing appropriate conditions for both test and demonstration purposes. Before applying the method no solutions had been provided to realise the assembly. Assembly systems were implemented to solve the test case problems. The following can be summarised from the CMM stylus assembly case:

- The design and assembly process selection procedure is supported by the DFµA methodology

- Design features have been influenced (gripper handle, joint design, capillaries for glue depositing, chamfer etc.)

In terms of verification the following conclusions can be drawn from the minifluidics test case:

- The usefulness of a structured DFμA approach has been made evident when looking for a joining process and adapting the design of the product.
- Applying the methodology in the *conceptual design stage* saves time and cost (see Figure 85). That is, for the test case presented here, development time and cost could have been saved on the injection mould by attending earlier in the process to issues related to the mould's design. No further design iterations and reworking were needed.

These conclusions highlight the notion that the methodology created as part of this research serves its intended purpose. Although the methodology still relies on human reasoning and interaction, it has been shown to provide important support for the design and process selection. So far, the decision-making has been left to the designer and done by considering the suggestions provided in the process sheets. Automating decision-making was considered as outside the scope of the research because it was felt that there is sufficient research in that area which can be transferred to address this problem. The results of this initial verification have been positive. Critical microassembly process characteristics can be captured in a systematic way which in turn supports the selection of processes. The methodology provides a framework to capture and evaluate microassembly guidelines, and also provides an initial basis of solid guidelines which have been used in addressing the two test cases.

7.4.2 Outcome of verification and discussion of results

The research results provide microproduct designers with a transparent and structured approach to looking at their microproduct designs and microassembly processes. The results of the initial validation show that the developed methodology will support the designers and process engineers in their day-to-day work. The system shows the potential for significantly accelerating the process from designing microproducts and -parts to planning their assembly. Accordingly, there is huge economic potential justifying further research in this area. The framework for microassembly databases enables the systematic capture of microassembly process characteristics, allowing experts to access, assess, and apply this knowledge. It has been clearly shown that the structured approach assists the designer in a number of ways, these including:

- Providing support of process selection
- Enabling the collecting and accessing of DFμA guidelines
- Allowing the accessing of process characteristics
- Offering support in the conceptual design stage
- Facilitating a shorter time to market

8 Conclusions and outlook

Due to global pressures, manufacturing in Europe is facing ever more challenges such as increasing demands with regard to time to market, lower production and product cost. In defining the scope for this thesis, it has been explained that microproduction can be seen as of strategic importance for the European manufacturing industry (see section 2.1).

For companies in the micromanufacturing sector it is critical to introduce innovative microproducts to the global market to differentiate themselves from the global competition. In addition to this challenge which appears similar to those existing for conventional production, the microsector faces a unique problem: the potential of a wide range of industrial MST applications is only shown by the development within research environments of demonstrator products which have not yet been or cannot yet be transferred to industrial practice. Consequently, the overarching aim of this thesis is to help overcome the barriers between single research products and production on an industrial level by developing a DFA methodology for the microdomain.

The focus on microassembly results from its significance for the micromanufacturing sector. Microassembly is necessary for the fabrication of three-dimensional products that are characterised by a high degree of complexity and the need for multi-material products. Furthermore, assembly constitutes a large part of microproducts' manufacturing cost (as outlined in section 2.4.2).

The product development and the product design processes have been reviewed with consideration paid to specific characteristics inherent to the micromanufacturing sector (see section 2.2). This was followed by a comprehensive review of the state-of-the-art in microassembly, particularly focussing on key processes such as microhandling, -feeding, and -joining (see section 2.3). It has been shown that microproduct design and -assembly would benefit from a DFA approach specifically focussed on the challenges appearing in the microworld (see section 2.4).

The knowledge gaps have been identified by analysing the state-of-the-art of DFμA and highlighting the limitations of conventional DFA methods with regard to the microworld (see sections 2.5 and 3.1). They are based on *the relevant needs in the area of microassembly, the shortcomings of existing DFA, and the present lack of sufficient DFμA methods*. Section 3.1.2 clearly outlines that a structured approach is necessary to assist the designer in developing MST products. There is a need to consider microassembly process features in early design stages and there is no sufficient support in the selection of suitable microassembly processes at present. Furthermore, evidence has been provided to show that there are not enough adequate design rules and guidelines focussed on the microworld.

The knowledge gaps identified are addressed by the key developments of the thesis, such as the microassembly process capability model (see Chapter 4), a procedural DFμA methodology (see Chapter 5), and a model for microworld-related guidelines (see Chapter 6). Chapter 7 illustrates and provides initial verification of these developments by showing them in software implementation and applying them to two practical test cases.

After clarifying the importance of the topic and objectives, and giving a brief summary of the work carried out, the following sections will

- Discuss the originality of the key developments, highlighting their contribution to existing knowledge while evaluating the contributions' impact and limitations (section 8.1)

- Conclude by outlining what opportunities for future investigation are provided by the work presented here (section 8.2)

8.1 Key knowledge contributions

The main objective of the work was the development of a DFμA approach that supports product design and process selection enabling the assembly of complex three-dimensional miniaturised devices. This research objective has been addressed through the key developments made in this thesis (as described in chapters 4, 5, and 6), which at the same time contribute to and expand the existing *focal and data theory*.

A *microassembly process capability model* has been developed to *support the DFμA methodology*. It provides a general framework to model and encapsulate the capabilities of the microjoining, -feeding, and -handling processes. The model is a core component of the DFμA approach, enabling the matching of the design of microparts and their assembly processes. It is envisaged as 'open-source', allowing third parties to add their processes' capabilities. The microassembly knowledge can be used by the designer at an early stage of the product development process, leading to more efficient product developments as the need for design reworking is avoided.

The *DFμA methodology* connects and bridges different design phases, providing an overall organisation to translate the microassembly capability model into practical application. The methodology takes existing microdomain challenges into account, thereby overcoming the current limitations of conventional DFA methods as identified here. The main functions and stakeholders (client, product designer, equipment provider and manufacturing engineer) of the DFμA environment have been modelled in UML (on the basis of use cases). The key phases represent the methodology's functionality: reaching from the conceptual microproduct design over the microproduct analysis to the analysis of microassembly process routes.

The derivation and development of design rules and guidelines that are focused on the microworld and its specific challenges has been an additional research objective to support the DFμA concept. An approach to evaluate existing guidelines has been developed and applied. Guidelines that aim at enabling assembleability and facilitating easy assembly of microproducts have been collected and developed. These guidelines can be used to direct product design and optimisation as well as selection of processes.

The developments have been applied to two relevant test cases taken from what are for the UK strategically important sectors. The initial validation results show that the methodology can support designers and process engineers in their day-to-day work. The DFμA methodology shows the potential to significantly accelerate the whole process from designing microproducts and parts to planning their assembly. It has been clearly shown that the structured approach assists the designer in a range of ways, enabling and implementing the microassembly of the two real life problems.

The work carried out extends the existing knowledge in the area of designing assembly-oriented microproducts. PHILLIPS AND PUGH and FRANCIS have analysed a range of ways in which research programmes can show originality (Phillips and Pugh, 2005, Francis, 1976 cited in Phillips and Pugh). Their analyses have been used to justify the classification of the work carried out as original. The results are summarised in Appendix G, Table 10 that shows different ways of achieving original contribution to knowledge and classifies aspects of this research according to their model.

In conclusion it can be said that the application of the developed DFµA concept can indeed support the designer in a systematic way in developing microproducts from early stages in the design onwards, making sure that the product parts can be fed, handled, and joined. This consideration of microassembly constraints can result in a range of benefits such as reduced time to market, development and assembly cycle time, re-use of existing microassembly processes, and higher quality due to adaptations in the product design with respect to process selection and layout. This is particularly important because an ignoring of assembly-related aspects in the design stage often results in the failure of the entire project. Although exact cost and time savings cannot be quantified yet, there is huge economic potential justifying further research in this area.

8.2 Future work

The thesis extended the current state of knowledge in microassembly-oriented design, overcoming existing limitations in the area. Nonetheless, due to the complexity of the field, it is impossible to solve all existing problems in the area through the research carried out here. This section aims at outlining future work that can be carried out with respect to DFµA by building on the contributions presented in this, the first monograph developing a body of assembly-oriented design knowledge specifically for the microworld.

It is clear that any research regarding product design in the microworld cannot be carried out without considering assembly technologies, processes, and their characterisation. The development of the microassembly capability model lays a foundation by providing a general framework for the characterisation of microassembly processes. The validation showed promising results in helping with the designing of microproducts and implementing appropriate microassembly systems.

Automated process selection and sequencing as well as automatically generated design suggestions are very complex areas and should be subject to future research for microassembly-oriented design. The DFμA methodology opens up new possibilities for the integrating of such automatic reasoning approaches. That methodology and its constituent parts allow for extensions such as case-based-reasoning, expert systems, or other artificial intelligence (AI) approaches.

Further development of the MS Windows-based application tool could potentially result in a powerful expert system providing and disseminating the implicit knowledge of experienced designers and process engineers either within a company or across whole industrial sectors.

It can be confidently said that the DFμA methodology outlined here has, and has been shown to have, a very real potential for real-world application. What is importantly characteristic of the approach is that it constitutes a heuristic system, such that it is necessarily improved by its being visited and revisited: made more powerful by its being put to work, as ever greater contributions and refinements are made to the knowledge base the system makes available to those using it. What is envisaged, then, is that the model should be widely employed in industrial settings, where it can improve itself as it improves the quality, speed, and efficiency of microproduct design and fabrication.

Appendices

A – Tabular description of use cases

System boundary	Use case	Description of use case	Involved stakeholders
Requirements specification and conceptual design	Define product requirements	The client typically provides the *product design specification*, i.e. listing the requirements but not the specification of the product itself (it is essential not to describe the product itself at this stage because that would restrict the possibilities for the actual product design).	Client
	Develop principle solution	Based on the specification given by the client the product designer develops a product that meets the demands of the client. That is, first the designer develops a principal solution based on the product requirements defined in consultation with the client.	Product designer
Design for microassembly environment	Analyse the product's assembleability	The product's assembleability (general product structure) is analysed, and the design is updated accordingly.	Product designer
	Apply DFµA guidelines to optimise the design solutions (including the conceptual product design)	DFµA guidelines are applied to the conceptual product design. The designer should familiarise himself with the appropriate guidelines and assess his conceptual design against them. DFµA guidelines are derived, developed, and described in Chapter 6, and an outline of how they can be applied is provided as well.	Product designer
	Provide assembly capabilities	The process data provided (including indications on fixed and variable costs) enables the design team to directly compare the cost of different assembly processes. The equipment provider possesses microassembly process knowledge and provides information about the assembly capabilities of the equipment, such as relevant data on accuracy, repeatability, speed, cost, applicability (materials, environment etc.), and so on. The manufacturing engineers provide assembly process capabilities for company owned assembly equipment and customised developments for which data is not publicly available.	Equipment provider, Manufacturing engineer (system integrator)
	Analyse product design against assembly process capabilities	The analysis of the product design is carried out with regard to assembly process capabilities, which are provided by external (OEM) or internal equipment providers, i.e. the	Product designer

		company's own manufacturing engineers or subcontracted system integrators. The process capability model introduced in Chapter 4 gives the equipment provider a means of characterising the processes in a structured way.	
	Evaluate qualitative assembly process costs	Design adaptations related to the candidate microassembly processes can be considered before involving the manufacturing engineers or engaging with an external system integrator to plan and implement the actual assembly system (production planning and control).	Product designer
	Select assembly processes	Manufacturing engineers or an external system integrator are engaged to plan and implement the actual assembly system (production planning and control).	Product designer, Manufacturing engineer (system integrator)
Production planning and control	Obtain assembly process chain	The manufacturing engineer (or system integrator) determines the assembly process chain in detail and implements the assembly processes.	Manufacturing engineer (system integrator)
	Implement assembly processes (production)	Once the product design has been optimised and the microassembly processes selected, the manufacturing engineers or system integrators need to acquire and install the assembly equipment.	Manufacturing engineer (system integrator)

B – Description of complexity levels C1-C6

	Part properties that indicate low complexity	Part properties that indicate high complexity
C1	• No flexibility • No fragility (not sensitive to the exertion of any forces) • No contact-sensitive surfaces • Simple shapes (cube=6 surfaces) • Joining, handling, or feeding features available for the part • Defined surface or points available that can serve as references for the microassembly process	
C2	• No flexibility • No fragility (not sensitive to the exertion of any forces) • Joining, handling, or feeding features available for the part • Defined surface or points available that can serve as references for the microassembly process	• One contact-sensitive surface • More complex shape (more than 6 surfaces, but cubical)
C3	• No flexibility • No fragility (not sensitive to the exertion of any forces) • Joining, handling, or feeding features available for the part • Defined surface or points available that can serve as references for the microassembly process	• More than one contact-sensitive surface • More complex shape (more than 6 surfaces, *non-cubical*)
C4	• No flexibility • Defined surface or points available that can serve as references for the microassembly process • Joining, handling, or feeding features are not designed into the part	• More than one contact-sensitive surface • More complex shape (more than 6 surfaces) • Certain areas are fragile (sensitive to the exertion of a forces)
C5		• More than one contact-sensitive surface • More complex shapes (more than 6 surfaces) • Joining, handling, or feeding features are not designed into the part • Defined surface or points are not designed into the part. So there are no references for the microassembly process available • The part is to a certain degree flexible • Certain areas are fragile (sensitive to the exertion of a forces)
C6		• High degree of flexibility • High degree of fragility (sensitive to the exertion of any forces) • All surfaces are sensitive to contact • Complex shape (pyramidal structure, round shapes, cube shape >6 surfaces) • No features to help the joining, handling, or feeding process • No surface, feature available that can serve as datum point or surface • Necessity for bio-compatibility of materials to be used

C – DFA/DFμA guideline analysis

Category	Breakdown of conventional DFA guidelines	Applicability to DFμA
Reduce the total number of parts	The reduction of the number of parts in a product is the best opportunity for reducing manufacturing costs:	Many points still valid, but in some cases the part reduction brings more difficulties than benefits as the comparison below shows.
	fewer purchases	Since quality is important and small variations could have large influences, it can be useful to keep all parts from one batch (of a specific fabrication process) together. That is, enough parts produced in the same batch under the same circumstances should be stored collectively.
	less inventory	In terms of space less important, since microparts do not take up much space. In terms of bound costs, still true. Additional factors, such as required clean room environment, steady temperature, and controlled humidity, this can be of importance and so cause increased cost.
	less handling	True, in particular under consideration that the orientation of a micropart should not be lost. But it could be possible to replace one difficult to handle/feed part with two easier to handle parts.
	less processing time	Fewer parts could be more complex, so the processing time could increase.
	less development time	True
	less equipment engineering time	True
	less assembly difficulty	It could be possible to replace one difficult to handle part by two easier to handle parts.
	fewer service inspections	Fewer incoming components inspection.
	less testing	True
	How to find non-necessary parts:	
	A part does not need to have relative motion with respect to other parts.	In the microworld the products do not consist of as many parts as assemblies in the macroworld do. The microproduct is built by exactly following the functional design. Those designs are not based on older designs so it is not very likely to happen, that unnecessary moving parts are included. New rule: Design

		only by considering the exact functional design.
	A part does not have to be made out of different materials.	The point of the DFμA methodology is to enable multi-material assembly. For silicon-only made parts still true. In the microworld the temptation of using different materials for no reason is extremely low. Only reasons are due to functional requirements and cost.
	A part which makes the assembly or service of another part difficult or impossible should be removed.	True, bottlenecks (in various senses) should be analysed in detail for better overall performance.
	Some approaches to part-count-reduction are based on the use of one-piece-structures and the selection of suitable manufacturing processes like injection moulding, extrusion, castings etc.	Down to certain scale true. Etching processes might become dominant.
Develop modular design	The use of modules in product design simplifies manufacturing activities such as inspection, testing, assembly, purchasing, redesign, maintenance etc.	True, but due to too little "high volume" production not useful. Platform technology like used in car industry could help, e.g. standardised connectors for sensor or actuators.
	Reasons for cost reduction:	
	Modules add versatility to a product-update in the redesign process.	True for products made of many components and component subassemblies, seldom the case in microproducts
	Modules help run tests before the final assembly is put together.	True but testing of modules is not that important as in large scale products, which consist of many modules.
	Modules allow the use of standard components to minimise product variations.	Limited/no standard components in the microworld, not even standardised equipment available.
	The connection can be a limiting factor when applying this rule.	True, especially, as connections take space. This fact can limit miniaturisation.
Use of standard components	Standard components are less expensive than custom-made items.	Limited/no standard components, e.g. no screws.
	Advantages:	
	High availability of standard components reduces product lead times.	MST products are very complex and specific. Currently the products themselves do not even move from the research laboratory to industry
	Reliability is ascertained.	false, see above.

	Production pressure is outsourced to supplier.	Quality assurance is very important, having parts from different batches can cause problems. In house production might be sensible.
Design parts to be multi-functional	Multi-functional parts reduce the total number of parts in a design, thus obtaining the benefits given in rule 'reduce total number of parts.' Examples:	Outstanding importance, but consider objections of rule 'reduce total number of parts' (see above).
	Part acts as both electric conductor and structural element,	True, especially for miniaturisation and integration.
	Original function plus alignment features to facilitate assembly.	Very important
Design parts for multi-use	Different products can share parts that have been designed for multi-use.	Compromises in the design are much harder to get in the microworld than in the macroworld.
	It is necessary to identify parts that are suitable for multi-use.	Would be helpful, but hard to realise.
	The aim is a set of standard part-families from which multi-use parts are created.	Would be useful, but hard to realise.
Design for ease of fabrication	Select the optimum between material and fabrication processes to minimise the overall manufacturing costs.	True, might be nice in the early design stage, if different materials are necessary, assembly has to be considered.
	Final operations such as painting, polishing, finish machining etc. should be avoided.	Mostly not needed, impossible in microworld anyway. Rule not necessary.
	Excessive tolerance, surface finish requirements etc. are commonly found problems that result in higher production costs.	Microworld inherent, cannot be avoided, should be assured- maybe by focussing the attention on them. As precise as necessary-check potential for optimisation. In general, production costs are higher in the microworld.
Avoid separate fasteners	The use of fasteners increases the cost of manufacturing a part, due to the handling and feeding operations that have to be performed.	True, especially because feeding and handling of small parts is difficult and more expensive.
	Fasteners should be avoided and replaced by e.g. snap fits.	True, fastening not always possible.
	Minimise number of fasteners.	True

	Minimise size of fastener.	Microfasteners only
	Minimise variation of fasteners.	
	Utilise standard fasteners.	No standards available
	Avoid screws that are too long, short, separate washer, tapped holes, round and flat heads (not good for vacuum pick up).	Screws only exceptional, 1mm, in watch industry down to 0.3mm.
	Self-tapping and chamfered screws are preferred because they improve placement success.	True
Minimise assembly directions	All parts should be assembled from 1 direction.	True
	If possible, the best way to add parts is from above, in a vertical direction, parallel to gravitational direction (downward). In this way, the effects of gravity help the assembly process, contrary to having to compensate for its effect.	Not true! In the microworld, gravitation is not so important, more important: tolerance, fitting, cohesion, etc.
Maximise compliance	Errors can occur during insertion operations, due to variations in part dimensions or on the accuracy of the positioning device used. This faulty behaviour can cause damage to the part and/or to the equipment.	No/minimum variations in part dimensions. Use parts from same batch/tool/mould, e.g. microinjection. High accuracy tools, that are expensive. Coarse/fine alignment. All dimensions should be 100% known in the microworld.
	It is necessary to include,	
	Compliance in the part design,	Still true
	Compliance in the assembly process	High accuracies tools, that are expensive.
	Examples of part build-in-compliances features:	
	Tapers and chamfers	Still true, if possible
	Non-functional external elements to help detect hidden features.	Not desirable, because it hinders miniaturisation.
	Examples of compliance for the assembly process are:	
	Selection of a rigid base part	True
	Vision systems	Necessary, e.g. for closed loop control
	Use of high quality parts with designed-in-compliance,	Self-evident

	Rigid base part	Still true, often the assembly takes place on a substrate
	Selective compliance in the assembly tool.	Coarse/fine steps
Minimise handling	To facilitate orientation symmetrical parts should be preferred wherever possible.	Reducing complexity is important in the microdomain. However, it can be difficult to realise symmetrical parts when the objective is to miniaturise parts.
	In case symmetry is not possible the asymmetry must be exaggerated to avoid failures.	Not possible for microdevices (but they can be fed in certain orientation).
	Use external guiding features to help the orientation of the part.	Due to sticking effects the use of classical external guiding features (contact-based) is difficult. However, tailor-made solutions (e.g. V-gooves for glas-fibre cable alignment or self-alignment approaches) are possible. Batch feeding and parallel assembly due to larger substrates can utilise such guiding featurs too.
	The subsequent operations should be designed so that the orientation of the part is maintained.	Extremely important. Gripping and releasing is a difficult task in microassembly. A basic rule should be to 'never lose orientation of a part'
	Also magazines, tube feeders, part strips etc. should be used to keep this orientation between operations.	Extremely important, particularly magazines seem to be a suitable feeding approach. However, there are no standards and they have to be tailor-made for each component.
	Avoid using flexible parts-use slave circuit boards instead.	True
	If cables have to be used, then include a dummy connector to plug the cable (robotic assembly so that it can be located easily.	E.g. glass fibres, connecters, handling of glass fibres
	When designing the product try to minimise the flow of material waste, parts etc. in the manufacturing operation.	True
	Take packaging into account, select appropriate and safe packaging for the product.	Important, no contamination, fragile, maybe orientation

The conventional DFA guidelines analysed in the table above (first 2 columns) are taken from and based on (Chang *et al.*, 1997 as cited on *http://www.granddragongroup.net/zl/5.pdf*)

D – Pool of DFµA guidelines in tabular form

Checklists can be used to implement the guidelines listed below. By this means the designer can determine a product design's weaknesses or flaws in a systematic way. A major advantage is that checklists can be easily applied and customised in a range of different industrial areas according to a company's needs. Therefore it is advised to monitor technological advancements in microassembly in order to utilise them within the product development.

	DFµA – Guidelines D = Product design related DFµA guidelines P = Process design related DFµA guidelines M = Milieu related DFµA guidelines	**Supporting information for designers (tooltips)**
	Orientation	
P	Know and closely control/monitor the components' orientation.	Losing orientation and/or requiring reorientation will lead to either decreased reliability or increased cycle time and thus is costly.
P	Maintain the orientation of parts/components when passing them to subsequent operations.	
P	Constrain the part when the orientation needs to be changed (e.g. transport to the next station).	
P	Secure the component by another mechanism before releasing it from a holding mechanism.	In this way the sticking effects can be prevented from disrupting the assembly.
P	Keep the number of orientation changing operations to a minimum.	Every required change of orientation is accompanied by a risk of losing the desired orientation or losing the exact information regarding the orientation.
P	Limit the number of process steps requiring reorientations.	
DP	Selected assembly processes in such a way that the product to be assembled is at the centre, with the required processes clustered around it.	The reduced need for the product to change position or be reoriented leads to certain benefits in terms of reliability, such as reduced risk of misalignment (caused by sticking effects) and reduced possibilities of losing orientation.
PD	Aim at a product structure (when designing) that reduces the number of processes in/for which reorientation is necessary.	
P	Design feeders in a way that they provide a defined part orientation (e.g. cavities, magazines).	This allows for accurate pick up and the reduced need for object recognition.
P	Use fixtures that can *'save'* current part orientations.	Fixtures are important in the microdomain because precise alignment and location accuracy of workpieces are crucial to the success of microassembly processes.
	Complexity	
D P	Limit the complexity of both the assembly system and the product and part design.	This can be understood as necessary in order to avoid failures and increase reliability.
D	Investigate the whole product system, not	This is necessary to get an optimised

	only the functioning individual components.	solution of the overall system.
D	Increase *functional* integration wherever possible.	Reduces the assembly processes and can decrease cost and risk of failure.
D	Split parts (thus decreasing their complexity) to avoid handling difficulties.	Enables the designer to introduce features into parts that support microassembly (see guidelines on alignment features, sticking effects, or joining).
D P M	Relate design, fabrication, and assembly closely: Answer the questions 'how to manufacture a product?' and 'can the product be manufactured and assembled?' simultaneously.	In the microworld it is even more important to work on process and product design in parallel/simultaneously than is the case in the macroworld.
P M	Assure accessibility for the assembly tools, e.g. gripper and glue dispenser (Scheller, 2001).	Part features and influences from the integration of microassembly process need to be considered
M	Consider the material properties of the product components and the gripping mechanisms and their relation to environmental conditions.	The effects of these properties and mechanisms (e.g. temperature or humidity) can make it necessary to very closely control the environment.
D P	Adapt either the grippers according to the product geometry or certain part features to the gripping principle.	This avoids failures during the gripping and releasing process. In addition it can support achieving the required accuracies.
	Quality	
M	Decouple microassembly processes from environmental influences (e.g. vibration).	This increases consistency and quality (accuracy) of the microassembly process
M	Decouple microassembly processes from other –processes (e.g. part feeding) to avoid cross-impact.	
D P	Analyse the tolerance chain, including the component tolerances resulting from the manufacturing processes and the assembly tolerances resulting from feeding, handling, and joining.	Varying component tolerances can render the subsequent microassembly processes impossible. Assembling without self-alignment features results in a direct dependency on the whole tolerance chain of the assembly and part manufacturing processes.
D P	Define part and process tolerances accurately.	
D	The principles of *PokaYoke* should be applied if necessary and possible.	This prevents certain mistakes from occurring by making the design and assembly '*fool-proof*'.
M	Use clean room environments when necessary (try to avoid the need for costly clean rooms through intelligent microproduct design to reduce the cost).	Due to small sizes and tolerances, particles or swarf can lead to misalignments or functional failures (e.g. current conducting small pieces could cause short circuits).
P	Run machine capability tests when setting up the assembly system to learn about the number of defective parts (probability of defective parts) and put appropriate inspection methods in place (probability of defect discovery).	This assures predictability of process performance. The designer can use this information to introduce necessary measures (e.g. alignment features, reference points) to avoid low quality.
P M	Make sure tactile testing processes do not contaminate the product, consider optical processes for quality assurance.	Risk of contamination.
P	Do not exert high forces on the components to avoid misalignment.	Risk of damage and misalignment.
P	Make sure fixtures are not exerting high forces on the components.	
	Alignment features	

<table>
<tr><td>D</td><td>Make use of the principle of self-alignment e.g. through part-inherent geometries and mechanisms.</td><td rowspan="5">Self-alignment mechanisms are in general based on defined geometries.
The components to be assembled are characterised by matching features on both parts. Basically, one part contains a positive feature whereas the second part holds the negative feature. This solution allows the using of less accurate handling processes, which in turn decreases the system cost whilst increasing its efficiency.
Passive structures represent mechanical stops or elastic elements which position or align the microparts in accordance with the required accuracies. They are characterised by tolerances of only a few micrometres (Brecher et al., 2006). V-grooves, for example, are commonly used to align glass-fibres.</td></tr>
<tr><td>D</td><td>Make use of the principle of passive alignment.</td></tr>
<tr><td>D
P</td><td>Develop alignment mechanisms with defined negative forms and stoppers and adapt them to the respective task, using geometries as simple as possible (Scheller, 2001).</td></tr>
<tr><td>D
P</td><td>Integrate principles for positioning support during the assembly process, to realise a defined position and orientation of the components to be mated (Scheller, 2001).</td></tr>
<tr><td>D
P
M</td><td>Exploit other dominant forces such as capillary forces to self-align components.</td></tr>
<tr><td>D</td><td>Control components' positioning with reference to external part features (e.g. geometry, structure, or pattern).</td><td>External part features with an image can be measured and processed. The resulting difference of nominal/actual value comparison within the spatial coordinate system is used to control/regulate the assembly process.</td></tr>
<tr><td>D
P
M</td><td>Assure detectability of components and their alignment features during the assembly process (Scheller, 2001).</td><td rowspan="3">These guidelines detail the requirements necessary to improve the alignment process based on external features.
Alignment features ease the dependency on the whole tolerance chain of part manufacturing and assembly processes and/or allow bigger manufacturing process variances for the components. The aligning and positioning of the parts is supported in a defined and controllable way.</td></tr>
<tr><td>M</td><td>Illuminate the components so as to realise sufficient contrast, necessary to allow for recognition of edges and sufficient measurement accuracy, e.g. when using visual measurement systems (Scheller, 2001).</td></tr>
<tr><td>P</td><td>Use positioning processes sufficiently accurate to align the components according to the target values (Scheller, 2001).</td></tr>
<tr><td colspan="3">Sticking effects</td></tr>
<tr><td>D</td><td>Contact electrification can be reduced through materials with small contact potential difference (Fearing, 1995, Böhringer et al., 1999).</td><td rowspan="5">These guidelines contain applicable strategies to overcome adhesive effects

Surface-related forces, such as van der Waals forces, surface tension forces, and electrostatic forces have a far greater effect than the gravitational forces that in this context are essentially negligible.

Because of this scaling behaviour, handling in the microworld distinguishes itself from that in the macrodomain, particularly when components to be manipulated are less than one millimetre in dimension.</td></tr>
<tr><td>D</td><td>Use conductive materials to reduce electrostatic effects, in addition the forming of insulating oxides should be avoided (Fearing, 1995, Böhringer et al., 1999).</td></tr>
<tr><td>D</td><td>Contact surfaces should be kept to a minimum, e.g. use rough surfaces, round contact points instead of areas (Fearing, 1995, Böhringer et al., 1999).</td></tr>
<tr><td>D</td><td>Favour hard materials over rubber and plastic due to a reduced likelihood of the deformation that can lead to increased surface area (Fearing, 1995).</td></tr>
<tr><td>M</td><td>Surface tension effects can be reduced by providing a dry atmosphere (Fearing, 1995).</td></tr>
<tr><td>D
P</td><td>Make use of adhesion effects: the adhesion between the substrate and the object must exceed the one that occurs between the</td><td>The gripping process depends on factors such as material type, surface properties, gripping forces, force control, shape of</td></tr>
</table>

	microgripper and the object (Cohn *et al.*, 1998, Zesch *et al.*, 1997).	interaction surface, cycle time, accuracy of gripping and gripper movement, sensitivity to adhesive forces, assembly environment, etc.
D P M	Consider factors coming from the part itself, the necessary gripping orientations, and the milieu in which the process takes place.	
D	Consider part features that support self-alignment when using adhesive bonding to accurately glue the component into the right position (based on Bark *et al.*, 1998, Van Brussel *et al.*, 2000).	Details related to means of overcoming sticking effects when releasing a part (open gripper). Within production and assembly, handling, that is positioning and gripping, remains a critical process. In particular, releasing (e.g. opening of gripper) and gripping (e.g. gripper closure) are critical processes, because sticking effects might cause a change in orientation.
D P	To mechanically release the object by locking it to the substrate or by stripping it off against an edge (Zesch et al., 1997), or by using needles to push the object (Bark *et al.*, 1998) a suitable element needs to be considered in the part design.	
D	When vacuum gripping is envisaged gas can be injected: gas pushes the part while taking away the gripper. Therefore a flat and stable surface needs to be designed into the parts to be handled (for the vacuum grippers) (based on Bark *et al.*, 1998, Van Brussel *et al.*, 2000).	
D	When utilising surface tension force to grip a part, it can be released by evaporating the adhesive liquid. To realise this, components have to be designed accordingly, i.e. for example heat-conducting materials have to be selected (based on Bark *et al.*, 1998, Van Brussel *et al.*, 2000).	
P	Vibrate grippers (Böhringer *et al.*, 1995).	
	Joining/ joint design	
D	Consider to integrate *functions* into the adhesive joint, such as: • Structural support or damping by means of adhesive layers (regulation of tension) • Conduction or insulation of electrical current • Conduction or insulation of heat • Adhesives can be transparent for light of certain wave lengths of or can be entirely opaque • Glue can be used for sealing • A few adhesives may also provide a certain degree of permeability for gases (based on Dorfmüller *et al.*, 2007)	The most important joining mechanisms in microassembly are based on adhesives Due to its positive properties, gluing is typically the most appropriate joining solution in microassembly. In terms of microproduct design, the different properties of glue can be used to integrate functions into joints, and thus into the products, without the need for additional parts.
P	Control both the volume of glue dispensed and the force exerted to make the joint.	When joining the parts with glue, self-alignment can be problematic, because the accuracy of the glue joint can suffer from the force exerted by the assembly system (sliding of the parts on the glue cushion).
P	When joining by adhesives, hold the component in place until the glue is cured.	
D	Integrate cavities for adhesives, to spread the glue evenly and avoid component contamination (Scheller, 2001).	

E – Characterisation of microassembly equipment used for NPL test case (instantiations of capability model)

X-stage

	Linear stage – Klocke Nanotechnik	Part design influences	System design influences
Resolution	2nm	Accuracy, self-alignment features,	passive alignment
Repeatability	<10nm	Accuracy, self-alignment features, passive alignment	Vibration, controlled environment
Workspace (Stroke, reach)	50mm	Dimensions, product structure	Integration of axis
DOF	1	Product structure, layout	Integration of axis
Payload	2kg	Material, geometry (mass)	
Speed (max)	5mm/s		Cycle time
Operational restrictions	horizontal operation		System integration
Equipment dimensions Length (stroke direction) Width (max) Height	 80mm 34mm 13mm		System dimensions, integration
Modularity (control, accessories)	combination with other stages possible. horizontal operation		System integration
Vacuum compatibility	yes		Resulting from part requirements (needed or not)

Y-stage

	Linear stage – Klocke Nanotechnik	Part design influences	System design influences
Resolution	2nm	Accuracy, self-alignment features,	passive alignment
Repeatability	<10nm	Accuracy, self-alignment features, passive alignment	Vibration, controlled environment
Workspace (Stroke, reach)	50mm	Dimensions, product structure	Integration of axis
DOF	1	Product structure, layout	Integration of axis
Payload	2kg	Material, geometry (mass)	
Speed (max)	5mm/s		Cycle time
Operational restrictions	horizontal		System integration

	operation		
Equipment dimensions Length (stroke direction) Width (max) Height	 80mm 34mm 13mm		System dimensions, integration
Modularity (control, accessories)	combination with other stages possible. Horizontal operation.		System integration
Vacuum compatibility	yes		Resulting from part requirements (needed or not)

Z-Stage

	Linear stage – Klocke Nanotechnik	**Part design influences**	**System design influences**
Resolution	2nm	Accuracy, self-alignment features,	passive alignment
Repeatability	<10nm	Accuracy, self-alignment features, passive alignment	Vibration, controlled environment
Workspace (Stroke, reach)	20mm	Dimensions, product structure	Integration of axis
DOF	1	Product structure, layout	Integration of axis
Payload	2kg	Material, geometry (mass)	
Speed (max)	5mm/s		Cycle time
Operational restrictions	horizontal operation		System integration
Equipment dimensions Length (stroke direction) Width (max) Height	 50mm 28mm 20mm		System dimensions, integration
Modularity (control, accessories)	Combination with other stages possible. Gripper and force sensor attachment possible.		System integration
Vacuum compatibility	yes		Resulting from part requirements (needed or not)

Gripper

	Microgripper - Klocke Nanotechnik	**Part design influences**	**System design influences**
Gripping mechanism	2 finger gripper	Material, dimension, shape, surface finish,	

		surface properties, fragility, surface sensitivity (contamination through contact)	
Resolution	2nm	Fragility, gripping alignment features	
Stroke	1.2mm	Dimensions	
Gripping force	50mN	Fragility	
Force feedback	not available	Fragility	
Payload	according to gripping force <50g	Material, dimensions (mass)	
Object size	1.9-2.1mm	Dimensions	
Equipment dimensions	40mm 28mm 20mm		System dimensions, integration
Modularity of tips	Yes. By laser cutting they could be customised, but naturally limited.	Gripping alignment features, part features to allow multiple use of single gripper	Diversity of parts (limitations on flexibility)
Vacuum compatible	yes		Resulting from part requirements (needed or not)

Characteristics of the joining process

	Glue dispenser - GLT	**Part design influences**	**System design influences**
Joining mechanism	Adhesive bonding. Pneumatic dispensing. Time controlled	Material, dimension, shape, surface finish, surface properties, surface sensitivity (contamination through joining medium)	
Joint size (joining area)	> 10µm² (due to minimum droplet size)	Dimension, shape	
Joining surface (shape, roughness, preparation)	clean, dry		
Joining strength (dependent on joint area)	not specified, depends on glue.	Materials, dimension, surface property, surface finish	
Curing	Air dry		
Speed	depends on curing time of glue and speed of positioning modules		Cycle time
Tension, stress	depends on glue yes/no, to what extent, N/mm²	Fragility, materials, accuracy	
Operating temperature	21°C	Materials	
Joinable materials	No restrictions	Materials	
Durability/life time	depends on adhesive		
Integration of	yes. See guidelines	Part shape, materials,	

function into joint (e.g. light, heat, electricity insulation or conduction)	on gluing	number of parts	
Equipment dimensions	Needle: 1mm diameter Syringe: 5cm x 1cm diametre		System dimensions, integration
Modularity (integration to stages or robotics,)	Can be attached to positioning units		System integration
Vacuum compatible	Yes		Resulting from part requirements (needed or not)

The glue dispenser has the following properties: It is able to handle viscosities from low to high. The period of dispensing glue from ranges from 0,0001 to 999,9999 seconds with precise pulse control for small glue dots or lines. It is equipped with a vacuum glue retraction option and displays time, pressure, and use of vacuum.

F – Characterisation of equipment used for minifluidics demonstrator (instantiations of capability model)

Gripper

	Microgripper - Klocke Nanotechnik	Part design influences	System design influences
Gripping mechanism	2 or 3 finger gripper	Material, dimension, shape, surface finish, surface properties, fragility, surface sensitivity (contamination through contact)	
Resolution	10µm	Fragility, gripping alignment features	
Stroke	5mm	Dimensions	
Gripping force	50mN	Fragility	
Force feedback	not available	Fragility	
Payload	according to gripping force <50g	Material, dimensions (mass)	
Object size	3-7mm	Dimensions	
Equipment dimensions	40mm 28mm 20mm		System dimensions, integration
Modularity of tips	Yes.	Gripping alignment features, part features to allow multiple use of single gripper	Diversity of parts (limitations on flexibility)
Vacuum compatible	yes		Resulting from part requirements (needed or not)

Process sheet – Ultrasonic welding

	Sonics & Materials' 40 kHz ElectroPress	Part design influences	System design influences
Joining mechanism	Ultrasonic welding	Material, dimension, shape, surface finish, surface properties, surface sensitivity (contamination through joining medium)	
Joint size (joining area)	in the range of μm^2, (limitations wrt max. size $1500mm^2$)	Dimension, shape	
Joining surface (shape, roughness, preparation)	clean, dry, degreased		
Joining strength (dependent on joint area)	not specified	Materials, dimension, surface property, surface finish	
Curing	not applicable		

Speed	<1s/weld		Cycle time
Tension, stress	heat introduction only in joint area, very limited suitable for small parts	Fragility, materials, accuracy	
Operating temperature	no limitations, hot plastics cannot be welded reliably	Materials	
Joinable materials	thermoplastic materials, limited metals aluminium (only for microapplications)	Materials	
Joint reversibility	No		
Joining geometry	3d to a certain extent		
Durability/life time	thin long parts could be damaged (break or undesired weld) through ultrasonic vibration (eigenfrequency)		
Integration of function into joint (e.g. light, heat, electricity insulation or conduction)	complete seal	Part shape, materials, number of parts	
Equipment dimensions			System dimensions, integration
Modularity (integration to stages or robotics,)			System integration
Vacuum compatible	Yes		Resulting from part requirements (needed or not)
Volume production	recommended		
Economics	cost-effective		

G – Originality of the research work presented

The following table shows different ways of achieving original contribution to knowledge and classifies aspects of this research according to PHILLIPS AND PUGH's model.

Table 10: Originality of the research work

Ways of showing originality in scientific research (Phillips and Pugh, 2005)	**Contribution of the PhD thesis (including a short summary and reference to appropriate sections)**
Carrying out empirical work that has not been done before	Existing DFA guidelines for conventional assembly have been collected and their applicability to microproduct design and microassembly has been analysed. Following these investigations the DFA guidelines have been classified as either unsuitable, limitedly suitable, or particularly useful (see section 6.2). In addition, based on the observations of the difficulties occurring in the microdomain (see sections 2.2, 2.3, and 2.4), microassembly-specific design guidelines have been formulated (section 6.3 and Appendix D).
Making a synthesis that has not been done before	A novel DFµA methodology supporting microproduct design and process selection has been developed (Chapter 5). This is supported by the development of an entirely original microassembly

	capability model (Chapter 4) and a collection of microassembly-specific design guidelines (Chapter 6).
Taking a particular technique and applying it to a new field	DFA is a commonly known approach for conventional assembly on the macrolevel. Existing DFA tools have been analysed and taken into account when developing the novel DFμA methodology. It can be stated that the existing idea of optimising product design in terms of its assembleability has been applied to a new field, in this case the microdomain of manufacturing. It has been clearly outlined that there is a need for specific DFA techniques tailored for microproduct design (see section 2.2) and –assembly (see sections 2.3 and 2.4). The limitations of DFA methods and the lack of existing DFμA knowledge have been described (see section 2.5 and 3.1).
Using already known material but with new interpretation	Microasssembly-specific problems have been analysed by some few commentators. Lack of standardisation and the occurrence of sticking effects for example are recognised problems in the microworld. However, these aspects have been only examined on individual bases. This thesis analyses technological and economical issues in microproduct design and –assembly in a holistic way forming the

	basis for the development of a DFµA approach (Chapter 2). The developments focus on microassembly process characterisation (section 4.4) to support microproduct design and process selection (section 4.3) to help ease these problems at low cost.
Being cross-disciplinary and using different methods	Although the scope of this thesis is focussed on microassembly-oriented design, concentrating on complex shaped, three-dimensional microproducts made from multi-materials, the work carried out covers a range of different disciplines applying different methods. One of the major challenges in the microworld is the need for knowledge from multiple disciplines such as physics (different physical rules become dominant in the microworld), microassembly processes (joining, feeding, handling), and their integration and automation (see sections 7.2.3 and 7.3.3 for the implementation of microassembly systems). Depending on the products to be designed and assembled, knowledge from further areas may be needed: E.g. for the practical test cases considered here, expert knowledge for the realisation of measurement and biomedical devices became necessary (see sections 7.2 and 7.3). To model the main parts of the DFµA environment UML

	(computer science) was used.
Looking at areas that people in the discipline have not looked at before	As is described in detail in section 2.5, there has been only limited work done in the field of microassembly-oriented design. As a result there is a lack of sufficient DFμA methodologies. Hence the work carried out can be classified as original and novel. This can be said of the methodological developments described in sections 5.2 and 5.3, the development of the microassembly process capability model (Chapter 4), and DFμA guidelines (Chapter 6).

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