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TOWARDS AN INTEGRATED FRAMEWORK FOR THE CONFIGURATION OF MODULAR MICRO ASSEMBLY SYSTEMS

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Abstract

The future of manufacturing in high-cost economies is to maximise responsiveness to change whilst simultaneously minimising the financial implications. The concept of Reconfigurable Assembly Systems (RAS) has been proposed as a potential route to achieving this ideal. RASs offer the potential to rapidly change the configuration of a system in response to predicted or unforeseen events through standardised mechanical, electrical and software interfaces within a modular environment. This greatly reduces the design and integration effort for a single configuration, which, in combination with the concept of equipment leasing, enables the potential for reduction in system cost, reconfiguration cost, lead time and down time.

This work was motivated by the slow implementation of the RAS concept in industry due, in part, to the limited research into the planning of multiple system reconfigurations. The challenge is to enable consideration of, and planning for, the production of numerous different products within a single modular, reconfigurable assembly environment. The developed methodology is to be structured and traceable, but also adaptable to specific and varying circumstances.

This thesis presents an approach that aims towards providing a framework for the configuration of modular assembly systems. The approach consists of a capability model, a reconfiguration methodology and auxiliary functions. As a result, the approach facilitates the complete process of requirement elicitation, capability identification, definition and comparison, configuration analysis and optimisation and the generation of a system configuration lifecycle.

The developed framework is demonstrated through a number of test case applications, which were used during the research, as well as the development of some specific technological applications needed to support the approach and application.

To my Dad, who always encouraged me to be the best I could be, and to have fun doing it.

List of Publications

Journal Publications:

Smale D, Ratchev S (2010), *"Enabling A Reconfiguration Methodology for Multiple Assembly System Reconfigurations"*, accepted for publication in the Elsevier Journal of Manufacturing Systems

Smale D, Ratchev S (2010), *"A Capability Model for Multiple Assembly System Reconfigurations"*, submitted for publication in the Emerald Journal of Engineering Design and Technology

Smale D, Segal J, Ratchev S (2010), *"Application of the Ultrasonic Welding Process to the Manufacture of a Micro Fluidics Device"*, submitted for publication in the Elsevier Journal of Manufacturing Processes

Fully Refereed Conference Papers:

Smale D, Ratchev S (2010), *"Application of a Methodology for Multiple Assembly System Reconfigurations"*, Published in the proceedings of the 5th International Precision Assembly Seminar, 14-17 February 2010, Chamonix, France

Tietje C, Smale D, Haley S, Ratchev S (2010), *"Analysis of the Applicability of Design for Microassembly Theory to Biomedical Devices"*, Published in the proceedings of the 5th International Precision Assembly Seminar, 14-17 February 2010, Chamonix, France

Smale D, Haley S, Segal J, Ronaldo R, Ratchev S, Leach R K, Claverley J (2010), *"Utilisation of FIB/SEM Technology in the Assembly of an Innovative Micro CMM Probe"*, Published in the proceedings of the 5th International Precision Assembly Seminar, 14-17 February 2010, Chamonix, France

Smale D, Ratchev S (2009), *"A Reconfiguration Methodology for Multiple Assembly System Reconfigurations"*, Published in the procceding of the 4th ASME International Manufacturing Science and Engineering Conference, 4-7 October 2009, West Lafayette, Indiana, USA

Smale D, Ratchev S (2009), *"Enabling a Reconfiguration Methodology for Multiple Assembly System Reconfigurations",* Published in the proceedings of the 7th International Conference on Manufacturing Research, 8-10 September 2009, Warwick, UK

Smale D, Ratchev S (2009), *"A Capability Model and Taxonomy for Multiple Assembly System Reconfigurations"*, Proceedings of the 13th IFAC Symposium on Information Control Problems in Manufacturing, 3-5 June 2009, Moscow, Russia

Smale D, Ratchev S, Segal J, Leach R K, Claverley J, (2009), *"Assembly of an innovative probe tip for micro-CMMs",* Published in the 9th International Conference and Exhibition on Laser metrology, machine tool, CMM and robotic performance, 30 June – 2 July 2009, London, UK

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Nomenclature

Abbreviation	**Expanded Term**
CAMARA	Capability-based Approach for Multiple Assembly system Reconfigurations and Analysis
C_{CN}	Consideration Capabilities
C_{EX}	Existing Capabilities
C_{MT}	Matching Capabilities
C_{PR}	Capabilities to Procure
C_{RQ}	Required Capabilities
C_{SP}	Surplus Capabilities
DOF	Degree of Freedom
FMS	Flexible Manufacturing System
MMS	Modular Manufacturing System
MSA	Microsoft Access
PCR	Product Correlation Ratio
PFD	Process Flow Diagram
PFT	Process Flow Template
PMR	Process Module Ratio
RAS	Reconfigurable Assembly System
R_{MAX}	Maximum Reconfiguration
R_{MEAN}	Mean Reconfiguration
R_{MIN}	Minimum Reconfiguration
TRS	Total Reconfiguration Score

1 Introduction

The future for manufacturing companies contains many uncertainties and unpredictable factors, resulting from changing market, socio-economic and political climates, that will substantially influence their operations. This will necessitate that manufacturers, particularly in high-cost economies, maximise responsiveness whilst simultaneously minimising the associated financial implications. Addressing this critical challenge has been a priority for a number of initiatives, as well as efforts, generally by organisations acting independently, to adapt existing techniques and processes.

The *Reconfigurable Assembly Systems (RAS)* paradigm has been proposed as a potential route to achieving a solution to the challenge of maximising responsiveness and functionality whilst also minimising cost. RASs offer the potential to rapidly change the configuration of a system in response to predicted or unforeseen events through standardised mechanical, electrical and software interfaces and a modular framework and environment. Thus the design and integration effort for a single configuration is greatly reduced, which enables the reduction in system and reconfiguration cost and lead-time.

However, industry has been slow to implement the RAS paradigm, despite the proposed benefits. One of the major hurdles to realisation and implementation of RAS is that there has been little investigation into the planning of multiple system reconfigurations, especially when utilising limited product information.

This thesis presents an approach that aims to support and enable the realisation of RAS. The approach consists of a capability model, a reconfiguration methodology and auxiliary functions. The approach enables the complete requirement elicitation, capability identification, definition and comparison, configuration analysis and optimisation, generation of a system configuration lifecycle and integration to external tools.

1.1 Motivation

This work is motivated by the need to deliver a methodology to enable the consideration of, and planning for, the production of numerous different products within a single reconfigurable assembly environment. Within the area of RASs, the nature of the system and the application will have a substantial impact on any methodology.

It is common for the design of an assembly system to be commenced before the product design has been finalised to ensure that the lead-time is minimised, even if this results in increased system development costs. Therefore, the conceptual level design of the assembly system becomes the most important to the overall success of the project.

System Integrators must demonstrate to the Customer that their proposed solution best meets the requirements. It is key to: a) minimise the costs incurred in quoting whilst not committing to an unprofitable venture, and b) ensure that the quote is as competitive as possible. By reducing the effort required to both design and integrate an assembly system, the costs incurred are reduced and thus the price charged to the customer can be lowered without affecting profit margins or system performance.

The issues and complexities faced in designing a single, conventional assembly system are significantly amplified when considering a system with multiple configurations. Modular architectures enable System Integrators to implement a new configuration relatively quickly as much of the system is standardised. Increasing the repetition and re-use of equipment will certainly reduce the integration effort and also the system cost (particularly when reconfiguring a system) and generally System Integrators strive to do this, but it does not necessarily constitute a formalised method or approach.

The current market and economic climate requires that System Integrators are, like most other companies, risk averse and so re-use of equipment, architectures, designs and even software is very attractive. In the future the ultimate extrapolation of a risk averse industry could implement complete shift-changes in the way in which assembly systems are procured and operated.

The concept of System-to-Service transformation has already been implemented within the defence and aerospace sectors. Governments and airlines are no longer willing or able to procure expensive equipment and maintain it themselves. Instead, they contract a manufacturer to provide them with the capability they require from the hardware; the onus is then on the hardware manufacturer to deliver reliable systems to provide this capability. Such a concept is gathering momentum within the manufacturing sector as well, not least being driven by those companies who have been forced into the transformation by their customers. The result of this would be that manufacturing equipment no longer has a single purpose for which it is procured. Instead, each equipment module will be used and re-used in different applications and potentially even different locations.

Significant production challenges are presented as the technologies used to deliver a single prototype will very likely be substantially different from those used to deliver the mass-produced variant. Many complex, high-value, innovative or medical-use products will go through a development life that involves several iterations and design changes. The volumes used will begin at one or two for basic evaluation, through small batches, service trial batches and finally to mass production.

The potential variations between the prototyped and mass-produced parts are large enough that if prototyped devices are used in the trials, the results may have no real meaning. Therefore, it is desirable to use devices produced in the same way and with the same line as the final mass-produced devices. This is rarely possible, due primarily to the large financial risk of implementing a production line without the guarantees of production sales. The lead-time associated with the design and implementation of a production line is an additionally prohibitive factor.

An additional level of complexity is that, in order to mitigate technological and financial risks, companies often undertake multiple product developments simultaneously. This may be in the form of multiple variants of the same broad product type, or it may be entirely different products. The RAS paradigm, combined with system modularity and an appropriate multi-product design methodology, would provide a means of addressing the challenges faced.

The most effective means of delivering this capability at a hardware level is the use of RASs. RASs can be reconfigured and are generally modular in their architecture. The standardised framework and rapid exchange interfaces are essential attributes in realising fast reconfigurations of a system and making short production runs economically feasible for manufacturers.

The ability to rapidly reconfigure a system in order to deliver a new product is one of the primary benefits of RASs and this is amplified when a system must be designed for multiple products. Furthermore, RASs offer a risk-averse industry substantially mitigated risks in design and integration by reducing the number of unknowns and variables.

However, despite the benefits offered by RASs and the synergy with the System-to-Service transformation ideal, industry has been slow to implement the paradigm. One of the major hurdles to realisation and implementation is that there has been little investigation into the planning of multiple system reconfigurations, especially when utilising limited product information.

To this end, this thesis will deliver a methodology that addresses the key issues associated with the production of multiple micro products within a singular modular, reconfigurable assembly system. Thus, the research conducted during this thesis is driven by the need to facilitate the implementation of RAS for multiple products within the context of risk aversion and cost minimisation.

In order for the RAS paradigm to be realised within the micro domain, it is necessary for a number of key technologies to be identified, developed (theoretically and practically) and implemented. Therefore, this thesis will further aim to consider, identify and propose technologies core to the implementation of the RAS paradigm within the micro domain.

1.2 Background

In considering the development of a new approach towards the realisation of multiple assembly system configurations, it is necessary to consider the context of industrially-based systems.

1.2.1 Current System Configuration Design Practise

The current design practice of assembly systems is outlined here to illustrate the need for a novel approach that specifically deals with system reconfiguration (and) with multiple products.

During the design of assembly systems, three main stakeholders are generally involved: *Customers*, *System Integrators* and *Equipment Suppliers*. *Customers* need an assembly system in order to produce their products, *System*

Integrators specify, design, integrate and deliver the required assembly system, and *Equipment Suppliers* design and supply the fundamental building blocks of an assembly system. The role of the System Integrator is of primary importance for the reported investigation as this is the stakeholder who makes the majority of the fundamental decisions affecting the system (using information gathered from the other stakeholders).

The System Integrator has the responsibility for taking the requirements and specifications provided by the Customer and designing an assembly system that meets all or some of those requirements. The primary requirements are defined around the product or products to be assembled, specifically the relationships between the component parts. The relationships, or ‘liaisons’, define the requirements for the joining element of the assembly, which are generally the most technically challenging aspects of the system. The definition of the components themselves has a direct bearing on the gripping and fixturing (linked to component geometry) and on the feeding (linked to component shipping method, required orientation).

Additional aspects of the design and specification, such as layout and line balancing, are again the responsibility of the System Integrator. Whilst the decisions taken will be made to, as far as reasonably possible, satisfy all of the Customer’s requirements, there is a large area of interpretation and potential variation in the system: there is more than one ‘right’ system. The topology of the product will have a significant impact on the process sequence, and the physical space available for the system on site will have an impact on the layout. However, the System Integrator’s experience and expertise will play a very significant role in the decisions made. Indeed, it is often within these, relatively subtle, differences of experience, expertise and understanding that a System Integrators Unique Selling Point (USP) will exist.

It is therefore highly important that the proposed approach does not mitigate, dilute or restrict this aspect of the process. In addition to these technical requirements, the system design is substantially influenced by the ‘management’ requirements: lead time, system cost, pay back period as well as other specifications such as the use or exclusion of certain equipment.

The System Integrator will have to go through several design iterations, usually with regular communication with the Customer, to arrive at a solution that, in their opinion, best meets the requirements. This is a direct result of the complexity of a large number of variables that must be considered in striking the balance of system performance versus system cost.

When the conceptual design has been taken to a sufficient degree of detail, the embodiment design phase can be commenced. This phase starts with the selection of the key functional equipment components. The main responsibility of the System Integrator during the embodiment design phase is to ensure that all of these separate functional elements are successfully and efficiently integrated into a single system.

System Integrators must demonstrate to the Customer that their proposed solution best meets the requirements: a fundamental aspect of this is ensuring that the cost to the customer is minimised. One key means of delivering this is through the reduction in design and integration effort. By reducing the effort required to both design and integrate an assembly system, the costs incurred are reduced and thus the price charged to the customer can be lowered without affecting profit margins.

The current market and economic climate requires that System Integrators are, like most other companies, risk averse and so re-use of equipment, architectures, designs and even software is very attractive. Thus most System Integrators have developed their own system architectures and design approaches to aid them in mitigation of risk and minimisation of design and integration effort.

1.2.2 Mass Customisation

Assembly is a major focus within manufacturing as by its nature it must accommodate the full range of product variations, which are the result of producers addressing the constantly shifting requirements of the marketplace. Certain market sectors, such as electronics, medical devices and aerospace and defence, are particularly demanding with respect to miniaturisation, increasing function density and reduced production runs. The result is that products are more complex but are produced for a shorter amount of time, meaning respectively, that assembly lines have a higher capital cost and a lower payback period. This ultimately leads to assembly lines that are substantially less cost-effective and pose a real financial risk.

The *Mass Customisation* paradigm is the ultimate extension of this situation. The concept is that as a result of either a need (such as a medical implant) or a desire (consumer electronics) each individual product must be tailored to suit differing requirements. Current technologies generally achieve this through one of two routes:

1) *Bespoke product design*. Each product is altered from the core design to meet the specific requirements and then produced. This is a slow and costly route and used only where necessity is the priority, for example surgical implants to replace lost bones. It also requires that each manufacturing or assembly stage be customisable. As a result these products are generally made manually.

2) *Modular product design*. The core product is identical but the framework has been designed to allow certain functions to be added or left out at will without major disruption. This is typified by the production of automobiles and personal computers. Whilst very efficient, there are still substantial lead-times for non-standard specifications and the assembly lines are generally larger and more expensive than would be required for a single product configuration.

The *Reconfigurable Assembly Systems (RAS)* paradigm has been proposed as a potential route to achieving a solution to the challenge of maximising responsiveness and functionality whilst also minimising cost. RASs offer the potential to rapidly change the configuration of a system in response to predicted or unforeseen events through standardised mechanical, electrical and software interfaces and a modular framework and environment. Thus the design and integration effort for a single configuration is greatly reduced, which, in combination with the concept of equipment leasing, enables the potential for reduction in system cost, reconfiguration cost, lead time and down time.

1.2.3 System-to-Service Paradigm

The concept of System-to-Service transformation has already been implemented within the defence and aerospace sectors. Governments and airlines are no longer willing or able to procure expensive equipment and maintain it themselves. Instead, they contract a manufacturer to provide them with the capability they require from the hardware; the onus is then on the hardware manufacturer to deliver reliable systems to provide this capability. Such a concept is gathering momentum within the manufacturing sector as well, not least being driven by those companies who have been forced into the transformation by their customers. The result of this would be that manufacturing equipment no longer has a single purpose for which it is procured. Instead, each equipment module will be used and re-used in different applications and potentially even different locations.

The most effective means of delivering this capability at a hardware level is the use of RASs. RASs can be reconfigured and are generally modular in their architecture. The standardised framework and rapid exchange interfaces are essential attributes in realising fast reconfigurations of a system and making short production runs economically feasible for both manufacturers and System Integrators.

1.2.4 The 3D-Mintegration Project

Whilst manufacturing process innovation is tackling the details of micro-capability integration [Desmulliez, 2005], the associated design problems to be tackled are not at all trivial:

- Designers need to be able to access, identify, understand, compare and select from a breadth of beneficial micro- scale physical processes and principles, and also to be conversant with their disadvantages.
- Designers need to transform physical principles, typically understood in planar form, into more effective 3D structures.
- Designers need to be able to navigate a product with either no, or a drastically reduced, parts hierarchy as components are limited in their minimum size by available technologies.

Designers will inevitably continue to face issues of cost control, materials selection, the process specification, quality assurance and reliability, but these are the province of concurrent engineering refinements ongoing within the micro- domain [Topham and Harrison, 2008]. These points provide the basis for the motivation of the 3D-Mintegration Project.

A number of "Grand Challenges" associated with manufacturing were identified by both the Integrated Manufacturing Technology Initiative (IMTI) and by the Engineering and Physical Sciences Research Council (EPSRC). The IMTI produced a report [IMTI Report (2000)] which identified and outlined several Grand Challenges for manufacturing success in the 21st century, these being: Lean, Efficient Enterprises; Customer-Responsive Enterprises; Totally Connected Enterprises; Environmental Sustainability; Knowledge Management; and Technology Exploitation. The EPSRC identified and funded, within the area of Innovative Manufacturing, four Grand Challenge projects with the intention of providing the participants to *"…develop their portfolios to address major research challenges with the potential for significant impact on national manufacturing priorities…"* [3D-M Project, 2010]. One of the four was the 3D-Mintegration project (3D-M).

3D-M was conceived to address the challenges posed by the continuing trends of product miniaturisation, functionality integration and production up-scaling. The core challenge is: *"…developing true 3D design and manufacture technologies and then transferring them from the research base to become commercially viable processes…"* [3D-M Project, 2010]. 3D-M identified that a major hurdle in commercialisation of products is transitioning them through the Technology Readiness Levels (TRLs) and that evaluation of a product requires it to be produced in a method that is, at very least, highly representative of the final mass-production method. This is however a major design, technological, logistical and economic challenge. The work conducted in this thesis has been performed within, and in consideration of, the 3D-M project. The main project aim of linking and structuring new and innovative microdevice production techniques into a coherent and unified approach is shared by this work.

1.3 Aim

The aim of this research is to ***develop a new decision-making framework that enables the configuration of modular assembly systems***. Specifically, this research will focus on the consideration of multiple configurations of one assembly system in order to deliver the most effective and efficient solution for the manufacturer. In order to achieve this aim a number of specific objectives shall be delivered, these being:

- To develop a new Capability Model to enable the identification, definition and comparison of capabilities.
- To formulate a Capability Taxonomy, which will provide a standard and structured definition of 'capability'.
- To propose a Reconfiguration Methodology to enable configurations to be evaluated, specified and validated.
- To develop a number of Auxiliary Functions that will support the overall approach.
- To Validate the developments and proposals through the utilisation of a number of test cases that are to be derived from research projects.

This work is principally aimed towards the micro domain, which is clarified in Section 2.1.2, and focussed within the mechanical aspects of reconfigurable systems, rather than the control.

1.4 Approach and Thesis Structure

This Thesis is divided into 8 Chapters and is shown in Figure 1-1. Chapter 1 provides an introduction. Chapter 2 provides a literature review. Chapter 3 describes the research approach. Chapter 4 details the Capability Model, whilst the Reconfiguration Methodology is described by Chapter 5 and the Auxiliary Functions in Chapter 6. Chapter 7 demonstrates and validates the developments through test case applications. Chapter 8 concludes the thesis and outlines further work. In addition, there are a number of appendices that contain supplementary information.

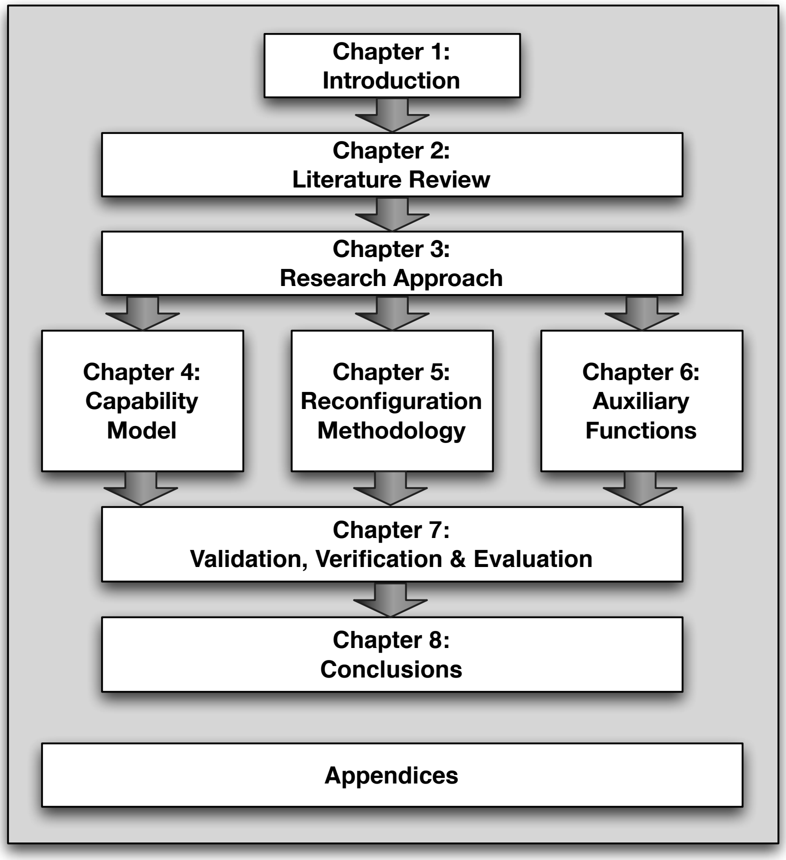

Figure 1-1: Representation of the structure of this thesis

2 Literature Review

2.1 Introduction

The Oxford English Dictionary defines 'assemble' as: *"[verb] to bring together into one place or mass"*. It further defines 'assembly' as *"[often as adj.] the action or method of fitting together the component parts of a machine or other object; the parts so assembled"* [OED, 2010]. This is reflective of both the term's common and technical usage; for the process itself as well as the results of the process. During the course of this work, these are the definitions that will be used. Additionally, 'system' is defined as *"a group of interacting elements forming a complex whole"* [OED, 2010]. Thus, an assembly system can be defined as a *"group of interacting elements that cause or enable the fitting together of component parts into a single product"*.

This definition draws the conclusion that an assembly system consists of three key elements: 1) the product being assembled, 2) the physical system performing the assembly and 3) the assembly processes themselves.

The assembly system itself, like the product, is made from a set of components, which are integrated in order to realise the functional system. These components have two broad types: equipment and structure. The general design process for a system is an iterative sequence of stages. The process is rarely completed in a single design iteration, not least as requirements are likely to change as a result of the preceding system design work. The first stage is to define the requirements in terms of functions needed. This is extrapolated from the information provided by the customer and from the product/s. This means that the requirements are driven from two key areas: the product and the business. The product defines the majority of the technical requirements that the system must meet; the business defines the parameters within which the system must conform.

These requirements are then linked to the physical system components that can deliver the required functionality. These will either be selected from equipment catalogues or custom produced for the application. With each of the individual components identified, it is then necessary to design or modify the supporting structure to accommodate these components. Once the complete system has been designed, it is then possible to project key indicators, such as lead-time (the time taken to deliver the system) and system cost. These numbers, along with the design, are presented to the customer who will approve or reject the design. The customer may agree to the alteration of requirements in order to change (usually reduce) one or more of the key system indicators.

Beyond the production of semicondutors and Printed Circuit Boards (PCBs), there is a clear lack of specificity in the future for conventional micro assembly as well as a lack of understanding of where the market is going [Heeren et al., 2004]. This is the result of the increased variety of processes and the three dimensional assembly characteristics that prevent the relevant technologies from fitting into a single framework. Furthermore, due to the high added value of the equipment required, dedicated production systems have become the common solution within industry, despite the inefficiencies and the impact upon product design and development [Puik and van Moergestel, 2010].

Manufacturing is moving away from the current lean manufacturing methods and approaches, and ever increasingly towards Mass Customisation, [Du et al., 2008]. Lean manufacturing is focussed on the delivery of large quantities of product quickly and cheaply [Bruccoleri et al., 2006]. However, customer expectations are increasingly looking towards the need and/or desire for bespoke products but delivered in time-frames and at costs common to mass-production.

The Mass Customisation paradigm is focussed primarily within industries that produce high value, highly regulated products that have long life cycles but are increasingly produced in small, highly customised batches [Jovane et al., 2003]. Typical industries include Medical Devices, Personal Care, Defence and Aerospace, which are coming to the paradigm from mass-production; other industries already deliver bespoke and short-run products but have not been required to deliver in quantities, these include Medical, Motorsport and the Space sector. All of these industries deliver and/or require products that have very similar specific requirements:

- The products are subject to constant changes, both deliberate and accidental.

- The products are high value.
- The products are highly regulated.
- The volume of production can vary substantially over time.
- The production is often limited to customised batches.
- The products are subject to stringent quality assurance standards.
- Full product traceability is essential.

The major challenge associated with the Mass Customisation paradigm is that of delivering an assembly system able to meet the highly specialised product requirements outlined above, whilst remaining economically justifiable.

The current state-of-the-art in manufacturing and assembly systems is that the vast majority of new lines are bespoke and single purpose. Generally, the system is designed to be as cost effective as possible, i.e. to achieve the required production criteria for the minimum cost and delivered in the shortest time [Mital and Pennathur, 2004]. This pressure is driven by the market, which demands that products are available quickly and cheaply. Both [Jin et al.,1995] and [Vos, 2001] note that manufacturers look to solve their immediate problems. There is, however, a growing awareness of the short-falls and short-sightedness of this approach.

Flexible Manufacturing Systems (FMS) offer one solution through the provision of enhanced capabilities and increased system flexibility. This enables the system to readily adapt to product changes, however it requires substantial additional investment as well as often leaving some equipment idle. Furthermore, the common focus of such systems is within manufacturing processes, such as milling and turning, rather than assembly.

Another proposed solution, which is assembly focussed, is *Reconfigurable Assembly Systems (RAS)*. RASs offer the ability to rapidly exchange process equipment modules through the implementation of standardised mechanical, electrical and software interfaces. By enabling the rapid exchange of functional modules, it is possible to facilitate a change in product quickly and efficiently. A major advantage of this approach is that only the equipment needed for each configuration is actually integrated, however the standardised architecture and interfaces do present limitations in terms of the range of layout and configuration options.

Whilst there have been substantial and sustained efforts in developing platforms that can be physically reconfigured [Du et al, 2008] and into appropriate control systems [Smith, 2000 and Dashchenko, 2003], there has been little investigation into the planning of multiple system reconfigurations. The full benefits of RASs are not being realised as they are not supported by a methodology that enables several system reconfigurations to be considered and planned.

In order to achieve the full potential offered by RAS, a new methodology must be developed that incorporates three key elements:

1. Capability taxonomy and definition process;
2. Capability modelling and comparison;
3. Reconfiguration identification, optimisation and validation methods.

2.1.1 Scope Definition

The overall research area and objectives have been defined in Sections 1.1 and 1.2, and the details of the literature overviewed in Section 2.1. Further to this, it is important to discuss and define the context and scope of this thesis. In broader terms, this thesis can be placed in the area of micro-manufacturing. This field is of great importance, particularly within European engineering, as highlighted by the Strategic Research Agenda (SRA) from the Eurpean Micro and Nanomanufacturing Platform (MINAM) [Ratchev and Turitto, 2008]: *"Micro and nanomanufacturing technologies might well be the next industrial revolution"*. This area is particularly reliant on technological innovations and so provides a pragmatic grounding for this thesis. This thesis is focussed towards micro, rather than nano; primarily due to the focus towards assembly rather than all manufacturing.

Assembly is *"the least understood process in manufacturing"* [Whitney, 2004]. Furthermore, Whitney continues that it is hard to define as it is a process we, as humans, simply do: we do not rationalise it in our minds. The abstract nature of assembly itself is compounded with the scientific challenges associated with the micro domain, which are detailed in Section 2.3.1.2. This results in estimates that up to 80% of production costs of micro products are as a direct result of assembly and handling [Koelemeijer Cholet and Jacoot, 1999, and Hesselbach and Pokar, 2000]. Further to this, the components themselves are difficult and expensive to produce as is the associated metrology [Leach, 2003]. This makes the majority of assembled micro products expensive.

2.1.2 Macro/Micro Boundaries

The primary purpose of this research is to deliver an approach focussed in micro products and their assembly within a modular and reconfigurable system. In order to do this, it is important to clarify the micro domain and its boundaries with the macro and nano domains. The use of the term “micro” is generally in reference to the dimensions of the product (including or limited to features and tolerances in addition to absolute dimensions), rather than the system (further described in Section 2.2.1.4).

There have been a number of works that have aimed to identify and define the precise realms of microtechnology. [Masuzawa et al., 2002] states that the state of the art in micromachining is for structures of less than 500 micrometres in dimension, whilst [Ferraris et al., 2003] considers that products with dimensions up to a few millimetres but with features and components in the micrometre range can be termed microdevices. However, [Alting et al., 2003] identifies that the issue of constraining microtechnology to pure dimensions is that the progression of the supporting technologies constantly alters (i.e. lowers) the boundaries from macro to micro. Thus the term *“microengineering”* is proposed. Microengineering is defined as dealing *“with the development and manufacture of products, whose functional features or at least one dimension are in the order of micrometres. The products are usually characterised by a high degee of integration of functionalities and components”* [Alting et al., 2003]. This definition is extremely relevant to this thesis as it encompasses the core features of any product that makes it a true challenge and suitable to be termed a microdevice.

Beyond and below microengineering and microdevices sits nanotechnology. The nano world is highly complex and often a mixture between engineering and chemistry as the scales are molecular. [Köhler and Fritsche, 2004] define nanostructures as having at least two dimensions below 100 nanometres, whilst [Corbett et al., 2000] describe nanotechnology as involving structures of less than 100 nanometres, where those features are essential to achieve the required functionality. Nanotechnology is not of direct relevance to this work, but it does set the lower boundary for the micro domain.

2.1.3 Critical Analysis

The literature reviewed in the preceding sections (2.1.1 and 2.1.2) has demonstrated a significant body of work, but is lacking in certain areas.

Assembly is, in many respects, not understood from a scientific perspective. This means that there is no singularly accepted route for description of how a product is assembled.

Whilst the overall cost and effort distribution of effort required to assemble microdevices has been described, there is no detailed description of the exact issues that cause these costs. Microdevices are considered and assumed to be inherently complex.

There is no definitive boundary between the realms of macro, micro and nano technologies or devices. This potentially causes different bodies of research to describe entirely different scales of product and tolerances within the same terminology.

The shift towards Mass Customisation is being slowed by the lack of suitable assembly solutions, to which RASs are presented as a potential answer.

2.1.4 Summary

This subsection has introduced the broad area of research in this thesis. Some of the key points are summarised below:

- Assembly is defined as consisting of three key elements: 1) the product being assembled, 2) the physical system performing the assembly and 3) the assembly processes themselves.
- The generalised design process for a system is an iterative sequence of stages: requirements definition, linking requirements to the physical system, system design and projection of indicators.

- The move towards the Mass Customisation paradigm is being driven by industries that require and deliver high value, low volume products.
- The products involved have certain typical requirements, which may impact the methodology used in delivering them.

2.2 Core Developments in Assembly Systems

2.2.1 Product Design and Development

One of the most fundamental aspects of a manufacturing or assembly system is the product(s) delivered by it. In order to design or specify a system, it is necessary to have some product details. However, in many cases, the product is designed and finalised before the relevant manufacturing system has been considered, leading to additional complexity, lead-times and cost. It is therefore important to aim to synergise any system design or specification tool with the product design process. There are several tools and methods, such as Design for Assembly (DFA) and Design for Manufacture and Assembly (DFMA) that aim to support such objectives, but these focus on altering the product design in order to improve the 'manufacturability' and 'assemble-ability' of the product. This section describes the type of products this thesis focuses on and the design processes and tools used in their development.

2.2.1.1 Product Design

Product design can be characterised as a process that results in sufficient data being available for the production of a particular product. [Slack, 2006] defines it as *"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"*.

It is widely recognised that the product design stage has a large influence on the overall production cost and success [Boothroyd et al., 2002 and Brown and Swift, 2008]. Further to this, changing product designs has a substantial impact the later in the stage it occurs: the earliest phases of the product design stage is the *"ideal and only time to get manufacturing cost right"* [Miles and Swift, 1998]. Design has a large impact on the production and operational costs as well as production lead times and quality [Pahl et al., 2007]. It is estimated that up to 80% of production costs are committed by the end of the concept design phase [Brown and Swift, 2008]. It should be noted that very little of this has actually been spent and so can be easily overlooked by designers, to the great detriment of the project and the company. The committal of this very high proportion of cost so early in product design supports the need for an assembly design tool that can operate alongside these preliminary stages.

2.2.1.2 Product Development Process

The design and development of products, as described previously, requires several stages be progressed through. There are a number of processes, tools and methods that can be used to facilitate the overall objective of delivering a product design.

The product development process comprises of four phases: *planning and task clarification*, *conceptual design*, *embodiment design* and *detailed design* and that these stages each produce progressively more detailed designs [Pahl et al., 2007]. *Planning and task clarification* considers the company environment and the market, identification of problems and gaps and the generation and selection of product ideas that meet the criteria. The result is a requirements list, often termed the 'design specification'. *Conceptual design* identifies the key problems and structures in the product and develops the working principles. This delivers a set of one or more product concept variants that need to be evaluated against the original criteria. Next, *embodiment design* evaluates and defines all of the main features of the product, delivering a definite layout, materials selection and a preliminary parts list. Finally, *detailed design* the engineering production drawings and final parts list are created, resulting in sufficient information for production to commence.

However, what can be noted is that production is only considered midway during the third phase: *embodiment design*. As previously highlighted, the majority of production costs are committed at a very early stage in the overall process. By delaying consideration of manufacture and assembly until relatively late in the process the potential for cost savings is reduced. Furthermore, even at the earliest phases of the process, innovation may be stifled into developing products perceived as ‘safe’ for manufacture – the lack of ability to consider assembly implications may result in sub-optimal solutions. In order to counter some of this problem, certain product design methods consider both manufacturing and assembly from an early stage.

2.2.1.3 DFA and DFμA

DFA is a representation of knowledge, procedures, analyses, metrics and design recommendations with the purpose of improving the product in the assembly domain [Whitney, 2004]. Whilst the traditional view was that engineers should have sufficient understanding and appreciation of manufacturing processes to account for the during product design [Tietje, 2009], the advances in manufacturing technologies, product complexity and market pressures (driving shorter product life-cycles and production lead-times) have necessitated that assembly itself be a focal point [Whitney, 2004]. The primary goal of DFA can be viewed as making assembly “easier, less costly, simpler and more reliable.” [Tietje, 2009]. Some methods, such as the *Boothroyd Dewhurst method* and the *Lucas method* are publically available [Mei, 2000]. Others are proprietary to particular companies and organisations, such as GEC, Fujitso, Denso, Sony and Toyota [Whitney, 2004]. Equally, software applications have become widely available to product designers and manufacturers.

All of the DFA methods and approaches described previously have been focussed in the macro domain. The micro domain, as described in Section 2.3.1.2, has a number of crucial differences that make assembly more complex. Thus, it must be asked whether conventional DFA methods are valid in microassembly [Eskilaender and Salmi, 2004]. The conclusion of this work is that the majority of DFA rules used at the macro level do still apply in the micro domain, but that critical areas, such as handling, feeding, gripping etc. require the inclusion and addition of new rules.

Some steps towards a DFμA tool have been made by [Salmi and Lempiaeinen, 2006], which highlights two key challenges in the implementation of DFA in the micro domain. The first is the technical limitations due to part size, the second is the broad range of technological solutions and the high rate of change. The authors acknowledge that *"the development of this tool is an iterative process"* [Salmi and Lempiaeinen, 2006]. This work has extended by [Tietje, 2009] into a more complete and coherent methodology and approach.

2.2.1.4 Microdevices

The field of this thesis is micro manufacturing and as such it focuses on micro-scale products and devices. Miniaturisation and integration of mechanical, sensing, and control functions within confined spaces is becoming an important trend in designing new products for commercial sectors such as medical, automotive, biomedical, consumer electronics, and telecommunications [Tietje and Ratchev, 2007]. However, the potential for micro-assembly for such products has been shown mainly in the research environment with a limited transfer of knowledge and equipment to industry [Ratchev and Koelemeijer, 2008]. These key commercial sectors require that the related products are manufactured to a very high quality and reliability [Peggs, Lewis and Leach, 2004]. This encapsulates the need for research into the area of microdevices

"Microdevices, which are characterised by incompatible or multi materials, and unsuited complex geometries, rely on assembly." [Tietje, 2009]. This description provides an insight into the complexities associated with the production of microdevices. Microdevices are often typified as silicon-based products, with both electronic and mechanical functions and features [Cecil et al, 2007]. Two notable terms are *"microsystems"* (MST) and *"micro-electro-mechanical systems"* (MEMS); [Senturia, 2000].

The 3D-Mintegration project was created in response to the need to develop true 3D design and manufacture technologies. Transferring them from the research base to become commercially viable processes is recognised as a Grand Challenge [EPSRC, 2010].

2.2.1.5 Design in the micro scale

The design of microdevices is very knowledge-intensive as it is characterised by a particularly high level of functional and component integration [Tietje, 2009]. Furthermore, there is a substantial lack of standardised parts and components for designs to call upon, which is due to the complexity of the devices, continual technological advancement and that the solutions are often highly application-specific. Standardisation of processes and components would reduce risk and potentially increase uptake, especially in the current risk-adverse market. [Leach et al., 2003] argue that this would in fact decrease market growth by restricting the potential for the recouping of the costs of the innovations that are key to the success of microdevices.

2.2.2 Equipment

An understanding of the key equipment types available in assembly automation is necessary for the development of an approach that considers them. Research in the area of assembly equipment focuses on two main areas: the development of new equipment solutions and the configuration/design of task specific equipment from well defined elements [Lohse, 2006].

2.2.2.1 Robotics

Table 2-1: Summary of the types of commercially available robots

Robot Type	**Sub-types**	**Key Features**
Articulated	Common variations of 2 to 10 axis Anthropomorphic robots offer 6 DoF to simulate the flexibility of the human arm	Rotary motor joints, fixed longitudinal sections
SCARA	With or without Z axis rotation	Simulates motion of human arm, restricted to the X-Y plane
Cartesian	Commonly used as two or three axis configuration	Linear axes in series, simple mechanical design and control principles
Parallel	Delta robot (three or four arms), Hexapod (six arms)	A kinematic chain of linear axes provides multiple degrees of freedom, including rotation

Within assembly, the most predominant equipment type is robots. Robots provide the motion of components and assemblies within (and occasionally between) workstations. With regards to current commercially available robotics, there are a vast number of suppliers and models. There are four broad categories of robot type, which are summarised in Table 2-1, which each represent a number of sub-types.

2.2.2.2 Gripping

Gripping is the physical principle that produces the necessary forces to obtain and maintain a part in a position with respect to the gripping device [Tichem et al., 2004]. Within the macro scale, the major force that is considered is gravity. Once in the micro domain, other forces become the major influences, as described in Section 2.3.1.2. [Tichem et al., 2004] give an overview of the principles of gripping.

2.2.2.3 Feeding

Feeders have the function of presenting parts that were previously randomly oriented to an assembly station at the same position, with the correct orientation and the correct speed. One of the most common feeders in macroassembly is the vibratory bowl feeder. The bowl feeder has many benefits, including a high reliability, low cycle time and ability to work with bulk volumes of randomly oriented parts. [Biganzoli and Fantoni, 2004]

2.2.2.4 Joining

Joints occupy space, are often less strong than the bulk material, require additional production steps and parts, and are often difficult to realise on these small scales. Although avoiding assembly and joining is the best solution [3D-M, 2008], it is often impossible due to technological and economic reasons. Techniques for joining include: mechanical fasteners, adhesive bonding, welding and soldering.

2.2.3 Communication

An automated manufacturing system requires the communication of large volumes of data at high speed, with excellent reliability. In order to integrate the communication needs of the various elements within the system, conventional approaches utilise a three-tiered hierarchy [Swales and Meng, 1999], which is shown in Figure 2-1. These three layers are *device-connection*, *equipment-control* and *information-management*. Communication networks that implement this approach are hampered by a number of associated problems, such as the necessity to translate data between layers, the use of networking devices that are compatible with the relevant specific protocol as well as comparatively high maintenance costs and complexities [Hung et al., 2004]. There have been efforts to reduce these problems through the implementation of a two-layer architecture by the Schneider Electric [Swales, 1999] amongst others.

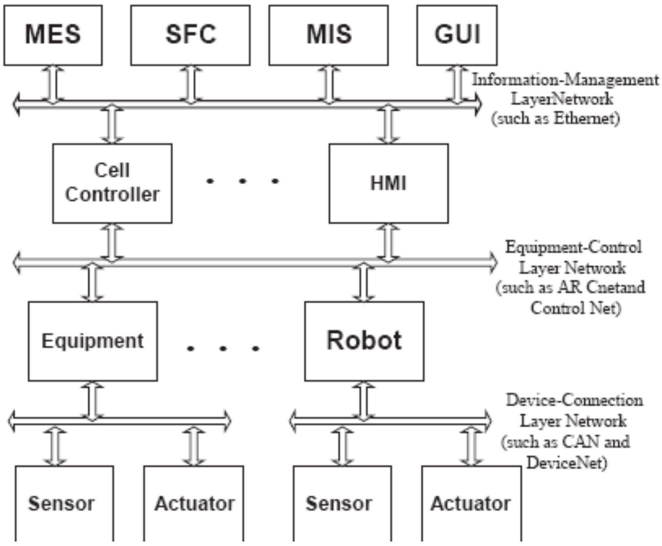

Figure 2-1: The three-layer hierarchical architecture of traditional factory automation networking, from [Hung et al., 2004]

2.2.3.1 Holonic Manufacturing Systems

One widely acknowledged communication concept is the holonic approach originally developed by [Koestler, 1968]. Holonic Manufacturing Systems (HMS) are a means of organising and orchestrating a manufacturing system. [Huang et al., 2002] state that HMSs utilise highly distributed control. The system is divided into elements, 'holons', which have both autonomous and collaborative properties and characteristics. A holon is an autonomous and cooperative building block in a manufacturing system that is able to create and control its own plans and strategies.

[Sugi and Maeda, 2003] propose a holonic assembly system, which assembles several components into products. [Leitao and Restivo, 2006] propose a holonic architecture for agile and adaptive manufacturing control. There are several other approaches, including [Babiceanu et al., 2005, Gou et al., 1998 and Jarvis et al., 2006], which all concentrate on scheduling the assembly process in a flexible way. However, they do not address the integration of a hardware independent control structure, nor do they consider the design implications.

2.2.3.2 Distributed Control

RASs require a control system that provides dynamic and fault-tolerant communication. This has lead to several approaches for distributed industrial control system. [Campelo et al., 1999] propose an approach which addresses the problem of fault-tolerance to ensure recovery when components fail. Others, including [Rostamzadeh and Torin, 1995 and Delamer and Martinez Lastra, 2004], have offered architectures that are distributed, fault-tolerant and have real-time communication. Another message-oriented publish-subscribe middleware is the Java Messaging Service, released by Sun Microsystems.

Further to this is the concept of Multi-agent Systems. The distributed characteristic of these systems enables them to be flexible and respond rapidly to changes, and as such agent-oriented systems have become very popular for the implementation of distributed manufacturing systems [Ferber, 1999].

Whilst these systems provide robust communication between many nodes, message-oriented communication is processor-hungry as well as being limited to the Java programming language. Critically, JMS does not support dynamic discovery of new components in a “plug and produce” manner [Joshi, 2006], severely restricting its usefulness in RASs.

2.2.4 Critical Analysis

The literature reviewed in the preceding sections (2.2.1, 2.2.2 and 2.2.3) has demonstrated a significant body of work, but is lacking in certain areas.

Product design has, for several decades, been highly formalised through the consideration of DFA methodologies. However, this has only very recently been specifically applied to the micro domain and to microdevices and has yet to filter into industry. It can therefore be assumed that microdevices are not optimised for production or assembly, thereby increasing the challenges associated with delivering them.

The DFA tools that exist, regardless of scale, do not show the implications and impact of the design with respect to the system required to deliver them. All methods rely on aiming to optimise the design efficiency of the product – this has not been specifically linked to efficiency of the system that produces the devices and therefore it cannot be conclusively stated that the improvements have helped. In addition, the lack of projected impact reduces the overall effectiveness of the methods and therefore it is possible that they are not being fully implemented as a result.

There is a very limited selection of equipment available for micro processing – that which is available is largely laboratory based. Hence, there are no standard procedures or systems for up-scaling of production of microdevices towards mass production.

2.2.5 Summary

This section has described the design core developments and features of an assembly system. Specifically:

- Product design consists of three core elements; psychological, systematic and organisational.
- The product design stage has a large influence on the overall production cost and success: it is estimated that up to 80% of production costs are committed by the end of the concept design phase.
- The product development process comprises of four phases and these stages each produce progressively more detailed designs.
- The primary goal of DFA can be viewed as making assembly "easier, less costly, simpler and more reliable".
- The majority of DFA rules used at the macro level do still apply in the micro domain, but that critical areas, such as handling, feeding, gripping etc. require the inclusion and addition of new rules.
- The production of microdevices is heavily reliant upon assembly.
- There is a clear gap in enabling and facilitating the development of microdevices, particularly for organisations with lower budgets and/or high risk aversion.
- Distributed control, particularly Holonic Manufacturing Systems and the Agent-based architecture paradigm, provides a robust approach, but lacks the real-time capability needed in advanced RAS.

- Several techniques aim to remove the assembly processes, but these are too limited in scope, application or readiness to be widely implemented.

2.3 Assembly Systems

2.3.1 Assembly

[Rampersad, 1994] defines assembly as bringing parts and/ or subassemblies together so that a unit comes into being, where subassembly is a composition of parts into a product unit. An assembly process is characterised by the manner and the sequence in which the product parts are put together into a final product. Moreover, the assembly process encompasses the operations: feeding, handling, composing, checking, adjusting and special processes.

2.3.1.1 Automated Assembly

Within the manufacturing industry, manual assembly is still surprisingly common, despite the availability and reliability of automated systems. The decision to implement manual instead of automated assembly may be driven by any one or a combination of the following factors, such as cost, variable/short production volumes or that the required tasks are too dextrous for automatic equipment.

In the case of high production volumes, automatic assembly is the most reliable and cost and time efficient means of delivering the products, especially in the case of the micro-scale. [Koelemeijer Cholet and Jacot, 1999] support this statement. The presented model of micro assembly systems cost finds that the cost of an assembly operation is the sum of the cost of feeding, separation and orientation as well as component and batch size, the results of which are summarised in Figure 2-2 and Figure 2-3. Figure 2-2 demonstrates that flexible microsystems are noticeably more cost effective than manual equivalents. Figure 2-3 maps product assembly cost for three different microsystems: manual, highly flexible assembly cell and a dedicated assembly line, finding that for all production volumes, automated assembly is more cost effective. System cost is highly important as calculations have shown that up to 80 percent of the production costs of miniaturised and hybrid systems are incurred during assembly [Koelemeijer Cholet and Jacot, 1999 and Hesselbach and Pokar, 2000]

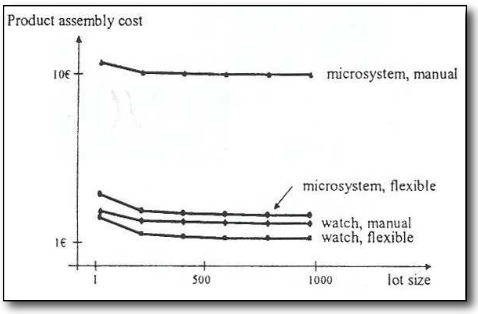

Figure 2-2: Plot of product assembly cost against production volume, from [Koelemeijer et al., 2003]

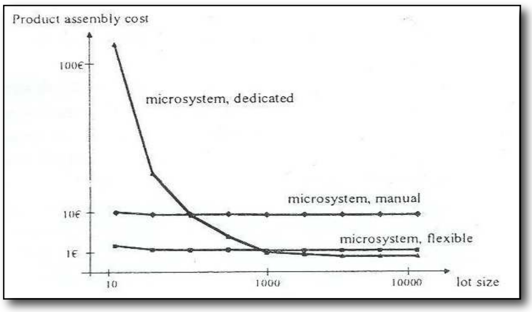

Figure 2-3: Plot of product assembly cost against production volume with specific consideration of dedicated lines, from [Koelemeijer et al., 2003]

The study "mikroPRO", [Hesselbach et al., 2003] reviews the international state of the art of micro production technology. The work identifies that the key driving factors for the automation of micro assembly systems are the development and provision of economically efficient, innovative assembly processes with greater accuracies and increased quality levels.

2.3.1.2 Micro Domain Assembly

Micro assembly is concerned with the assembly of small parts into systems, with high accuracy. Typical part dimensions are in the range of 100's microns up to ten or so millimetres, part features could be in the micrometer range, whilst the typical accuracies are in the range of 0.1-10μm.

The major difference between macro (i.e. conventional) and micro scale assembly is the required positional precision of the assembly equipment. Critically, direct hand-eye coordination is no-longer possible and so it is not possible to use workers as fill-ins [Van Brussel et al., 2000].

Another important difference is related to the mechanics of object interactions due to scaling effects. In the micro world, surface related forces, such as *van der Waals*, *surface tension forces* and *electrostatic forces* become dominant over gravitational forces [Van Brussel et al, 2000]. This scaling behaviour results in entirely different behaviour and manipulation requirements and strategies in the micro domain in comparison to the macro world.

Figure 2-4, from [Fearing, 1995], shows the different forces affecting an object in comparison to the object's radius. It is assumed that the object is a silicon sphere picked up by a gripper with flat jaw surfaces.

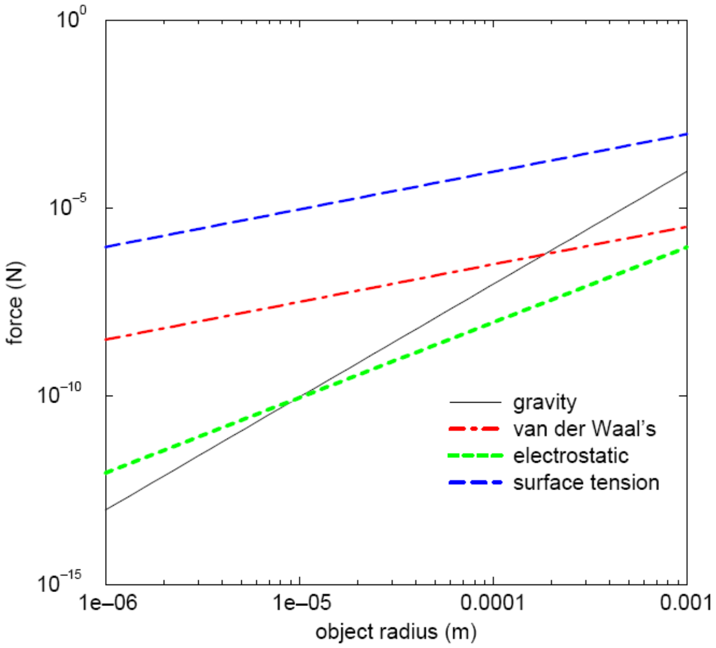

Figure 2-4: A plot of the forces acting on a sphere of varying radii, from [Fearing, 1995]

Potentially, these forces could be utilised to retain the object, but as they are very difficult to control or even predict, it is more likely they will have negative effects rather than positive. Furthermore, the major problem associated with these forces is releasing the object. The forces need to be reliable and consistently overcome so that the released part is correctly located.

2.3.1.3 Automated Micro Assembly

The use of manual assembly in the production of microdevices remains relatively common [Hesselbach et al., 2003] despite the challenges described in Section 2.3.1.2. The need for automation cannot be ignored: increasing complexity and miniaturisation requires the inclusion and integration of micromanipulation and automated assembly [Hollis and Quaid, 1995], whilst the benefits to cost, quality and lead-time of assembly automation, regardless of scale, cannot be achieved through manual production [Rampersad, 1994]. [Fatikow et al., 1999] highlighted that the realisation of automated microassembly facilities is essential for the continued proliferation of microdevices.

[Tietje, 2009] summarises the core of the challenge in this area: *"the requirements for automatic microassembly, in particular the processes and the equipment, are very dependent on the products to be assembled."* It must be concluded that any approach that aims to support microassembly system design and specification, must be product oriented.

2.3.2 Systems

2.3.2.1 Modularity

[Pahl and Beitz, 1996] state that products and assembly systems benefit from modularisation; it is a key approach in addressing the challenges posed by a dynamic market, which include increases in product complexity, changes to requirements, as well as the continuous addition of new or improved technologies, [Tsukune, et al., 1993, Bi and Zhang , 2001 and Stevens, et al., 1998]. Several sources consider that assembly system modularisation is a critical characteristic to facilitate the implementation and expansion of next generation agile system solutions, such as reconfigurable and evolvable assembly systems [Koren, et al., 1999, Onori, et al., 2002 and Hollis and Quaid, 1995].

"Modular products are machines, assemblies and components that fulfil various overall functions through the combination of distinct building blocks or modules." [Pahl and Beitz, 1996]. This definition offers an insight into the key feature of modularity: that high-level functions are physically decomposed to a set of lower-level functions reflecting the theoretical interpretation. The physical manifestations are known as 'modules': a term which can be applied both to products and systems.

Modularity itself is an approach that aims to define product or system architectures. proposes that there are two broad categories of architecture that can be identified: integral and modular. Two of the main approaches to both product and system modularisation are highlighted by [Pahl and Beitz, 1996]. Thus it can be established that modularity defines the relation between the abstract functions and the physical components [Ulrich and Tung, 1991 and Ulrich, 1995]. Modularity also relates the connections and interactions between the components themselves; the interactions between components in a modular architecture are defined through interfaces [Lohse, 2006].

2.3.2.2 Flexible Manufacturing Systems

Table 2-2: Summary of existing Flexible assembly and/or machining systems

NAME	YEAR	TYPE	OWNER	Ind or Acad
MARK II	1987	Robot	IVF-KTH	Academic
MARK IIF	1989	Robot	Atlas Copco	Industrial
MARK III	1993	Robot	IVF-KTH	Academic
DIAC	1994	Robot	TU Delft	Academic
RobotWorld	1979	Robot	Motoman	Industrial
GENASYS	1991	Robot	INFACT Machines	Industrial
EIMS-R	1993	Robot	Matsushita	Industrial
MAX	1992	Robot	IPA	Academic
APS	2000	AGV	Denso	Industrial
MART	1993	AGV	TU Delft	Academic
KAMRO	1993	AGV	U o Karlsruhe	Academic

The challenges posed by the production of products with frequent requirements and/or processing changes has led to the investigation and development of several different solutions. One form of solution that has received considerable research effort is Flexible Manufacturing Systems (FMS). This approach typically consists of designing an architecture which incorporates a large number of fixed capabilities, served by one or more highly flexible motion / transportation units [Vos, 2001]. Various groups have conducted research into FMS; usually there is a specific target or purpose for the system. There are several further examples of implemented systems, either robot or AGV based, which are summarised in Table 2-2.

One of the biggest issues in operating FMSs is that of communication. [Hung et al., 2004] present a developed potential solution where the focus is on the communication methods for FMS in general. Ethernet is highlighted as the best basis for the advanced communication necessary for networking, with the paper providing a novel solution for real-time data communication. [Neve and Plasschaert, 1996] made investigations into the potential standardisation of the communication structure.

The FMS approach creates two key problems: Firstly, the inclusion of multiple product variants to be manufactured in one system at one time presents huge logistical and identification issues. Secondly, there is, by definition, excess capabilities within the system at any given time. This represents uneconomic costs. The issue of logistics and data logging cannot be removed, but is an issue faced in most aspects of manufacturing where variants are involved. [Sujono and Lashkari, 2007] identify that material handling is in fact a major contributor to the overall cost of production (with respect to both lead-time and financially) within FMSs. The conclusion is that the FMS paradigm in fact worsens the economic situation in all but a relatively limited number of situations. In addition, the economics of excess capabilities standing idle is hard, if not impossible, to ignore.

2.3.2.3 Modular Manufacturing Systems

Modular Manufacturing Systems (MMS) offer the ability to rapidly exchange process equipment modules through the implementation of standardised mechanical, electrical and software interfaces. Within the context of this research, the primary focus is in assembly. Modular Assembly Systems (MAS) are a subset of MMSs, focussing on assembly operations. In reality, the majority of available MMSs are primarily concerned with assembly rather than ‘true’ manufacturing processes (such as turning, milling and grinding). Thus, for the purposes of this thesis, MMSs will refer to any modular system regardless of whether it is focussed on all manufacturing or assembly only.

MMSs are researched as a means of addressing the key issues presented by FMS, especially with respect to the excess capabilities [Vos, 2001]. MMS are systems whereby each equipment module (which has one or more capabilities) can be easily interchanged with another that offers different capabilities. This is typically achieved through the implementation of standardised mechanical, electrical and control interfaces. MMSs offer a number of key benefits: The standardised architecture reduces the design, simulation and integration effort, which in turn reduces lead-times. Furthermore, the modularity enables equipment to be easily and quickly exchanged. This maximises equipment reuse and facilitates the rapid reconfiguration of the system to allow for new products. Some examples of MMSs that have been implemented either in industry or as a research tool are summarised in Table 2-3. [Lohse, 2006] identifies that MMS are more widely accepted as the route for future production systems over FMSs due to:

- Their ability to meet system requirements at any point in time without exceeding them.
- The potential for rapid response to market and product changes.

Table 2-3: Summary table of Reconfigurable assembly and/or machining systems implemented as research tools

NAME	YEAR	TYPE	OWNER	Ind or Acad
SMART	1986	Modular Equipment	Sony	Industrial
Super SMART	1994	Modular Equipment	Sony	Industrial
LASSI	1999	Modular Equipment	Multiple	Industrial
Flexline	2000	Modular Equipment	Swatch	Industrial
Minifactory	1994	Modular Equipment	CMU	Academic

A significant research and development effort has being directed towards creating suitable system architectures for modular assembly systems [Boër, et al., 2001, Giusti, et al., 1994, Chen, 2001, Hollis and Quaid, 1995, Gaugel, et al., 2004 and Alsterman and Onori, 2001]. Modularity is one of the underlying technologies for reconfigurable and evolvable assembly systems.

[Hollis and Quaid, 1995] define a modular assembly system structure that is based upon cooperating 2-DOF robots. They stress the need for a highly automated rapid configuration method as one of the basic requirements for successful reconfiguration of modular systems. [Gaugel, et al., 2004] demonstrate a desktop assembly system that uses a modular architecture consisting of a series of relatively simple 2DoF planar motors and 2DoF manipulators for transport and assembly/feeding respectively.

[Barata de Oliveira, 2005] proposes a control approach that is coalition-based and investigates how changes at shop floor level can be accommodated by adaptations to a modular assembly system. [Lastra, 2004] reports a collaborative control approach, which enables modules to be controlled with greater ease within a modular environment. [Sugi, et al., 2001] propose a holonic assembly system approach that aims to minimise the configuration effort, but it is focussed on the addition only of manipulators to existing motion modules (i.e. robots). Whilst the approaches described offer solutions towards some of the control and implementation challenges associated with MMSs, they do not explicitly consider the wider design decision-making environment or methods for planning multiple system reconfigurations.

2.3.2.4 Available Systems

[Alsterman, 2004, Onori, et al., 2002 and Lastra, 2004] provide reviews of the commercially available examples of modular assembly systems, such as; the Sony SMART Cell, the ABB TUFF System, the Mikron Flexcell and the Feintool IMA Modutec. Many suppliers offer systems that can be flexibly configured, but the actual reconfiguration of these systems to deliver a new product (or a product variant) pose greater challenges. It is common for the system to have to be returned to the supplier for reconfiguration: this requires that the system be decommissioned, shipped to the supplier, reconfigured, returned to the manufacturer and re-commissioned; during which time production ceases and substantial costs are incurred [Puik and van Moergestel, 2010]. The authors go on to state that: *"If existing equipment would be gradually upgradeable, in a true reconfigurable sense, investments in equipment could be reduced significantly"* [Puik and van Moergestel, 2010].

2.3.2.5 Reconfigurable Assembly Systems

[Siemiatkowski and Przybylski, 2006] highlight that RASs are researched as a means of addressing the key issues presented by conventional systems. The reconfigurability functionality is typically achieved through the implementation of standardised mechanical, electrical and control interfaces. RASs are widely accepted as the route for future production systems [Hung et al., 2004].

There are a number of key benefits offered by RASs: The standardised architecture reduces the design, simulation and integration effort, which reduces lead-times and initial costs [Du et al., 2008]. Furthermore, the reconfigurability enables equipment to be easily and quickly exchanged and gives the potential for rapid response to market and product changes [Siemiatkowski and Przybylski, 2006]. This maximises equipment reuse and facilitates the rapid reconfiguration of the system to allow for new products.

Furthermore, RASs have the ability to meet system requirements at any point in time without exceeding them [Hung et al., 2004].

However, the full benefits of RASs are not being realised as they are not supported by a methodology that enables several system reconfigurations to be considered and planned. There has been some effort towards identification of requirements for new or reconfigured assembly systems [De Lit and Delchambre, 2003], the design of new assembly systems [Vos, 2001], operation allocation [Sujono and Lashkari, 2007] and equipment selection [Kulak et al., 2005]. However, the integration of all of these elements within a methodology that considers multiple system reconfigurations, and which is applicable both to new and to existing systems is not currently available.

2.3.3 System Design, Specification and Configuration

In order for any system to be realised, it is necessary for the relevant requirements to be specified, the appropriate configuration determined and the complete system designed. As stated previously, it is necessary for RAS to be product-centric, thus the first step towards the detailed specification of the system itself is to identify and specify the processes that it must deliver.

2.3.3.1 Assembly Process Specification

Assembly process specification is the process by which individual process steps for the production of a product are characterised, described and ordered. It is essential to provide some degree of formalisation to the processes, to apply a classification structure, a hierarchy and levels of detail that enable a domain specific interpretation of process models [Lohse, 2006]. Several approaches for assembly sequence representation have been developed, the most common forms being precedence relationships, directed graphs, and And-Or graphs. [Homem de Mello and Sanderson, 1991] identify that all of these are all inter-related and it is possible to convert the data from one form to another.

The sequencing of relatively high-level assembly tasks is a necessary step, but the sequencing process, as stressed by [Vos, 2001], must be decomposed further in order to capture sufficient information for equipment selection and detailed assembly line layout planning. To achieve the necessary level of detail, [Rampersad, 1994] proposed that individual assembly tasks be further divided into assembly operations that provide an accurate representation of the work to be performed by the system to assemble two components together. [Vos 2001] took this concept and applied divisions across eight main types, or classes. These being *Retrieve, Store, Grasp, Release, Move, Join, Fixture* and *De-fixture*.

By developing a classification structure that does not formally divide taxonomy and hierarchy, there is a degree of inherent flexibility enabling potential users to customise the system. Further to this, Lohse et al., 2003] propose that assembly processes be divided and structured using three hierarchical levels (tasks, operations, and actions) and that the classification be relevant and linked to the equipment side as well as the product/process side. [Barata de Oliveira, 2005] proposes that assembly processes are described through clustering or grouping of separate basic skills. Thus at a higher level, more complex skills are described, but at the lower level a comparatively small set of easily definable skills is needed

There has been substantial research into assembly process modelling, but there remains a need for a more comprehensive assembly process domain conceptualisations. Furthermore, as suggested and proposed by [Barata de Oliveira 2005, Lastra, 2004, Onori, et al., 2002 and Vos, 2001], assembly processes need to be decomposed, classified, explored and linked to both product and equipment oriented definitions of processes. By providing a dual-faced definition, effective and efficient comparisons can be performed, ultimately enabling a process model to become a core aspect of modular assembly system specification and reconfiguration.

2.3.4 Reconfiguration Levels and Mechanisms

Modular and reconfigurable assembly systems can be changed in different ways and at different levels. [Lohse, 2006] provides three levels for adaptation of a modular assembly system. These being:

- Level 0: Parametric changes – adapting the behaviour of available capabilities; e.g. changing the force settings of a pressing device

- Level 1: Logical changes – adapting the utilisation of available capabilities (skills); e.g. change of process sequences from one product to another
- Level 2: Structural changes – adapting the available capabilities; e.g. changing one process module for an other one or adding an additional assembly station

Level 2 is perhaps the classic interpretation of 'reconfiguration': physically exchanging equipment modules in order to deliver different system functionality. As a consequence, it is the most complex, requiring the highest degree of effort, but yields the greatest change. At the other end of the spectrum, Level 0 adaptation is the easiest to realise but also the least powerful. Level 0 adaptations can very often be realised in any assembly system, regardless of the modularity of the architecture. Figure 2-5 [Lohse, 2006] shows the principle levels of adaptation in a modular system. This thesis considers complete reconfigurations that alter the purpose of the assembly system; i.e. a change in product. This is most noticeably achieved through adaptations at Level 2, but will also involve Levels 1 and 0.

A configured modular assembly system will comprise of a number of equipment modules, each with one or more skills, which determine the available assembly process capabilities. The equipment modules are mechanically connected at Level 2. The overall process capability of the system is defined through the logical relationships of its module skills on Level 1. The specific process behaviour is defined through the parameter settings on Level 0 [Lohse, 2006].

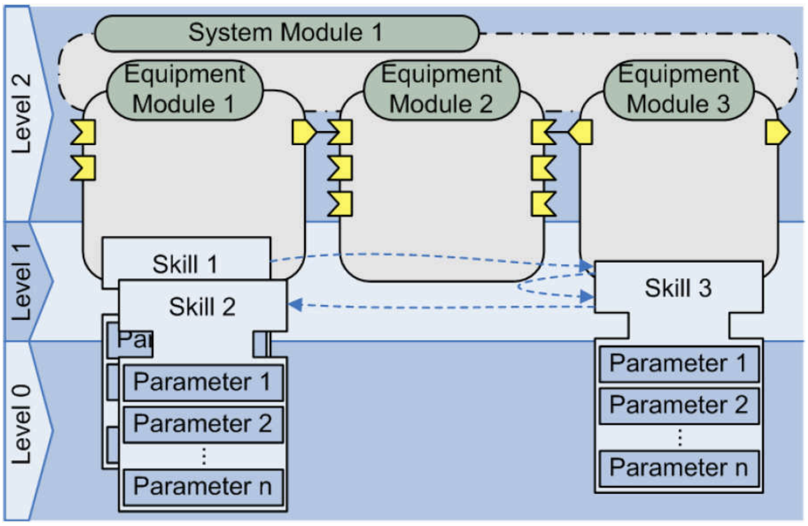

Figure 2-5: Principle levels of adaptation for RAS, from [Lohse, 2006]

Each of the levels of configuration require that a different mechanism be employed to realise them. This does not focus on the specific technicalities of the control realisation or the details of the mechanical architecture, instead it is concerned with the requirements that ultimately result in reconfiguration. The adaptation at Level 0 will require detailed evaluation of the processes, production data and take into account manufacturer information and geometries: it is system diagnostics. Typically, system diagnostics is conducted by experienced operators and integrators with the support of any hard and soft tools needed. This is not reconfiguration as defined within this work, but may yield results that indicate reconfiguration is necessary. Equally, it is likely to be required as part of the production ramp-up post reconfiguration. This research focuses on reconfiguration at Levels 1 and 2.

2.3.5 Design Methods, Methodologies and Models

2.3.5.1 System

An aspect of assembly system design that is investigated by [Graves and Lamar, 1983] is that there is a strong link between assembly tasks on the process side and workstations on the assembly system side. By considering workstations, the designer is able to focus attention on optimising the assembly processes in that area. By optimising each workstation, the complete system is improved but the engineers are able to focus on a series of relatively small segments of the problem to deliver the solutions.

[Pahl and Beitz, 1996] define the algorithmic design approach as a sequence of clearly defined stages that are completed during the process. Both [Stevens et al., 1998 and Tomiyama, et al., 1989] suggest that this highly structured method of design is often particularly beneficial in large engineering systems with inherent complexity. [Stevens, et al., 1998] illustrate the system engineering approach to design of complex products and system. The approach is more commonly used for complex products/systems but is not restricted to them. Such an approach is perhaps of increased importance when considering future system reconfigurations.

Equipment selection is itself usually composed of two stages: *conceptual selection* and *specific selection*. Conceptual selection is largely governed by the procedure outlined above; with the specific assembly processes grouped it is possible to associate an equipment type to it, for example: a SCARA robot and vacuum gripper. By selecting the broad type of equipment necessary for each assembly process, a schematic of the assembly system can be produced.

In a modular system, the architectural framework and compatible modules will often substantially limit the otherwise infinite number of possible solutions. The possible solution space is determined before a specific design problem arises [Lohse, 2006]. The decomposition process is aided by the implementation of a modular environment – the decomposition is linked to the modularity of the system. As a result, there are a finite number of solutions possible, even without defining the problem. These constraints can be used as an advantage by offering the potential to identify, at a very early stage in the system design process, whether or not the solution is achievable. This is a key gap and a major benefit within RASs.

[Koren, et al., 2004] identify that the natural progression from designing and implementing modular systems is system reconfiguration, with the primary difference being the need to accommodate the existing system. [Lohse, 2006] further proposes that new reconfiguration approaches must minimise the reconfiguration effort and cost. The new system capabilities must be efficiently realisable.

2.3.5.2 Assembly

All system design is reliant upon there being sufficient and structured data concerning the required assembly, delivered through assembly modelling and planning. Assembly modelling is primarily focussed on delivering a clear definition of the relationships between the individual parts that comprise the product. Assembly planning looks to identify the optimal solution (i.e. assembly process sequence) for a particular problem. [Homem de Mello and Sanderson, 1991] provide a summary of some of the research conducted within assembly planning and modelling.

[De Lit, 2001] provides a theoretical approach for the integrated consideration of a product family and the assembly system. The work suggests that assembly design, assembly sequencing and assembly line design be considered as concurrent activities to achieve the optimal results. This is furthered by [De Lit and Delchambre, 2003], who provide a more detailed methodology. [Rampersad, 1994] proposes another integrated approach that offers formal rules and guidelines for the integrated definition of assemblies, assembly processes and assembly systems.

There have been numerous research approaches investigating the feasibility of knowledge based [Travaini et al., 2002 and Zha et al., 2001], computer aided [Boër et al., 2001 and Bley et al., 1994] or assembly process description based system design [Rekiek, 2001 and Vos, 2001]. The reported approaches only focus on some decision-making aspects and do not yet address the specific modelling needs for rapid configuration and reconfiguration. Further to this, [Rekiek, 2001] presents an assembly line design tool that uses genetic algorithms to allocate tasks and equipment into workstations.

[Boër et al., 2001] reports the results from a specialised computer aided assembly-planning tool, which is primarily focussed in grippers and simulation. Further to this, there has been some concerted effort in utilising the internet as a collaborative/cooperative design and development environment [Chen et la., 2003, Denis et al., 2004 and Wang et al., 2003]. The objective is to enable project managers and designers to collaborate over the internet in the development and delivery of manufacturing systems.

MMSs provide scope for a development method that takes advantage of the key benefits of modularity. [Vos, 2001] proposes such a system, which considers the module specification and configuration processes to deliver a specification for a complete system. The research identifies *the matching of process requirements with the capabilities of the modules as one of the most critical problems that requires addressing*.

2.3.5.3 Equipment Selection

The appropriate selection of equipment modules to serve and meet the functional requirements is a fundamental aspect of system design, and this is equally the case with RASs. Traditionally, this is a very human-centred process, conducted by one or more experts. Efforts have been made to automate the process within research projects such as E-RACE and EUPASS, though neither have focussed specifically on multiple system reconfigurations. Kulak et al., 2005], have investigated the application of fuzzy logic to equipment selection.

Work within the area of Equipment Selection is relatively limited as the decision of which module to procure is generally made based on a cost-performance-availability basis and the assumption that these points are all known and fixed. The requirements for cost and availability are down to the customer specification, the issue of performance is generally made by a Capability Model.

2.3.5.4 Axiomatic Design

The axiomatic design principle proposed in [Suh, 1990] is that there are fundamental axioms controlling and influencing the design process. The principle is primarily composed of two axioms; *independence axiom* and *information axiom*, and of four domains; *customer domain*, *functional domain*, *physical domain* and *process domain*. All of the tasks within designing are contained in, and represented by, these four domains [Suh, 1995].

The axiomatic approach is one of abstract and mapping of requirements towards deliverables, but quantification of the factors is fundamental to determining the answer. The two overarching axioms have an impact on all design principles, including for RAS. The *independence axiom* requires that the independence of functional requirements be maintained, whilst the *information axiom* requires that the information content be minimised [Suh, 1990].

More recently, [Phoombolab and Ceglarek, 2007] have proposed a framework for a design, build and test procedure, specifically focussed on quality delivery through Six Sigma. The work considers interdependencies between design tasks in order to optimise their sequencing for the minimisation of simulation time. [Gu et al., 2001] proposed the margining of axiomatic and systematic design principle for the design of manufacturing systems. The process splits the design work into four design stages, which represent the four axiomatic domains. The work was applied to the design of an FMS, but ultimately concluded that the design process remains human-centric.

2.3.6 System Configuration

It is well established and recognised that the configuration of an assembly system has significant impact on its performance [Koren et al., 1998] and [Spicer et al., 2002]. The primary consideration during the configuration of RAS is the interfaces between the modules [Koren et al., 2001].

The work presented by [Wang and Hu, 2010] considers the impact of the complexity of the assembly system itself on the configuration, finding that increased product variety brings increased system complexity and reduced reliability.

The reconfigurability aspect of RAS results in the potential for frequent system changes, thus requiring that each new configuration be appropriately planned – in many cases this results in simulation of the configuration [Colledani et al., 2010]. This simulation can be very time-consuming and in the rapidly changing environment in which manufacturers operate, this time can be ill-afforded, further emphasised by the ‘changeability’ of a company. ‘Changeability’ is the ability of a company to rapidly and suitably react to external changes [Wiendahl and Heger, 2003] and this ability has an impact on both the strategic-level agility of the company as well as the low-level system reconfigurability [Koren et al., 1999].

There have been some considerable efforts in the modelling and quantification of assembly systems [Hallgren and Olhager, 2005] but this effort has focussed on the strategic level for managerial decisions relating to the business factors rather than the technical ones.

Some work has investigated the creation of an integrated control approach with modelling and configuration [Goh and Zhang, 2003], such work is based upon the agent-based control concept and concentrates on the control structure towards the realisation of an assembly system configuration rather than the physical aspects. Furthermore, [Koren et al. 1998] present the impacts of configuration on system performance, but the configurations referred to are the sequence of machining tools in a complete line rather than assembly modules within a workstation.

[Colledani et al., 2010] present a generalised and approximated analytical method which is intended to support the configuration and/or reconfiguration of production systems. It is generalised in that it considers reconfigurable, flexible and dedicated systems and does not require complex simulation, however the results are focussed on performance projections associated with overall product flow at the workstation level.

2.3.7 Critical Analysis

The literature reviewed in the preceding sections (2.3.1 to 2.3.6) has demonstrated a significant body of work, but is lacking in certain areas.

Whilst flexible micro automated assembly systems have been considered, there has been no specific research into the benefits or implementation of reconfigurable micro systems. The issue of variable or small production volumes is addressed only in the consideration of manual or semi-automatic micro systems – despite the identified issues associated with trying to achieve manual assembly in the micro domain.

The issues associated with forces in the micro scale, primarily regarding the non-dominance of gravity, have not been translated into an appropriate mitigation methodology. The issues themselves are identified in several texts.

The research effort and detailed development of flexible manufacturing systems has not been duplicated in the reconfigurable assembly systems area. The perceived reasons for this are that of communication and industrial need. Real-time communication is vital, but is now available. In addition; efforts in bringing microdevices to market is being hindered by unsuitable scalable assembly systems.

There are no available architecture-level standards for modular systems: there are standards associated with equipment-level interfaces (such as tool-changers), but these are insufficient for the realisation of a complete system. The development of modular systems would be further facilitated by the parallelised development of modular microdevices.

The decomposition of assembly processes, particularly with respect to the micro domain, have been insufficiently explored. This has prevented the development of approaches and methodologies with this core commonality – each new research investigation thus utilises a different process structure.

There has been little formalisation of the design process for assembly systems. This means that all system designers are following their own individual process – this is accentuated by the lack of standard architectures. There is in fact no commonality to the nature of the assembly design or upon what to base decision-making. A similar situation exists in equipment selection, which continues to be a human-centred process.

With regards to system configuration, there has been consideration of complexity and of modelling the results, but these are all based upon full detailed information being available – there are no methods for forecasting results utilising the limited information available at early product designs stages, which are agreed to be where the majority of costs are committed.

2.3.8 Summary

This section has provided a review of assembly systems, including automation and assembly specific to the micro domain, system design and specification and system types. Specific points include:

- There are several factors affecting the implementation of automated assembly systems, with upfront cost and inflexibility being typical hurdles.
- However, automated microsystems are demonstrably more cost effective overall than manual systems.
- Any microassembly solutions must be focussed on the product.

- Assembly process specification needs to be formalised in order to realise the potential benefits of RAS.
- Assembly process modelling requires structuring and simultaneously linked to both the product and to the equipment.
- The majority of existing system design approaches do not consider the specific configuration of a cell or workstation.
- A modular and/or reconfigurable system architecture will impact the configuration and design processes.
- Accurate representation of assembly processes within any approach is essential for successful design and specification.
- The matching of process requirements with the capabilities of the modules as one of the most critical problems that requires addressing
- Modular equipment solutions as one of the fundamental requirement for reconfiguration.
- With respect to assembly systems, modularity defines the relationship between abstract functions and physical components.
- FMS offer considerable functional flexibility, but with significant cost and levels of excess and unused capabilities that are unacceptable to industry.
- MMS offer the potential to ensure the correct level of functionality is available at all times through rapid exchange of equipment modules.
- RAS focus on assembly and typically, but not essentially, employ modularity to achieve reconfigurability.
- There is a lack of supporting technologies and methodologies in the implementation of RAS, such as:
  - configuration planning
  - existing system consideration
  - multi-product planning
- There is no singular method or approach towards the realisation of multiple reconfigurations for multiple production runs.

2.4 Models and Taxonomies

2.4.1 Ontologies

An ontology is concerned with the study of being or existence and their basic categories and relationships, to determine what entities and what types of entities exist [Lohse, 2006]. [Grunninger and Lee, 2002] highlight that ontologies aid in the clarification of knowledge structures, thereby improving all aspects of knowledge storage and sharing. There have been a number of ontologies developed with engineering applications, such as by [Borst et al., 1997 and Mizoguchi and Kitamura, 2000] as the knowledge structuring offers crucial benefits for design and decision-making environments.

2.4.2 Taxonomies

Taxonomies are the product of the process of scientifically classifying entities. Taxonomies are generally hierarchical in nature and as such are very useful in engineering applications. Within manufacturing systems, a taxonomy can be a means to enable and structure both the processes and equipment. Within MMSs, taxonomies can be used to define module types in line with the relevant architecture. [Pahl and Beitz, 1996] present a definition of module types with respect to their importance to the system and function; with functions being classified according to their role in the overall system. The work proposes synergies between functions and modules and lists four variants for a modular system: basic, auxiliary, special, and adaptive (reference Figure 2-6). Basic functions are the fundamental building blocks, auxiliary functions are additional or support functions for the basic functions, special functions are task specific sub-functions and adaptive functions are required for adaptation to other systems and to marginal conditions. In addition to this are customer-specific functions and are not included in the modular system.

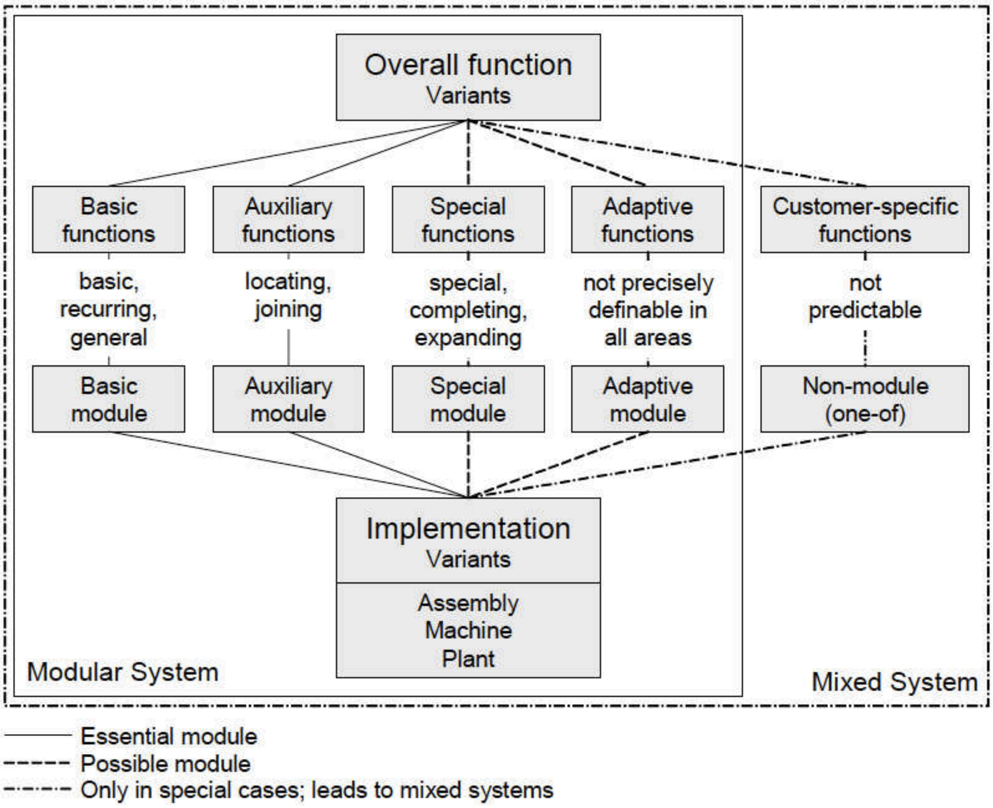

Figure 2-6: function and module types in modular and mixed systems, from [Pahl and Beitz, 1996]

[Bi and Zhang, 2001] present another taxonomy (reference Figure 2-7) that is focussed on manufacturing systems, providing a higher-level taxonomy for the classification of modular applications. The work is founded on that of [Ulrich and Tung, 1991, Pahl and Beitz, 1996] and others. This work proposes that any modular application should be defined based on four attributes associated to the components/modules and their interfaces. The type of components/modules of a modular application is classified by the type of component entities and at what level they are in regard to the overall application domain. Interfaces are defined based on how the components are integrated together (component view) and on how the connection between the components is being established by the interface (connection view).

Following the definition of modularity, two branches during the development of modular products and systems can be identified [Vos, 2001, Bi and Zhang, 2001]. Figure 2-7 shows the two branches. Branch 1 is the definition and design of a modular system and the subsequent development of specific modules. This branch has to take the requirements for all possible systems into account. The second branch takes requirements for one specific product/system and combines the existing modules into a suitable system configuration.

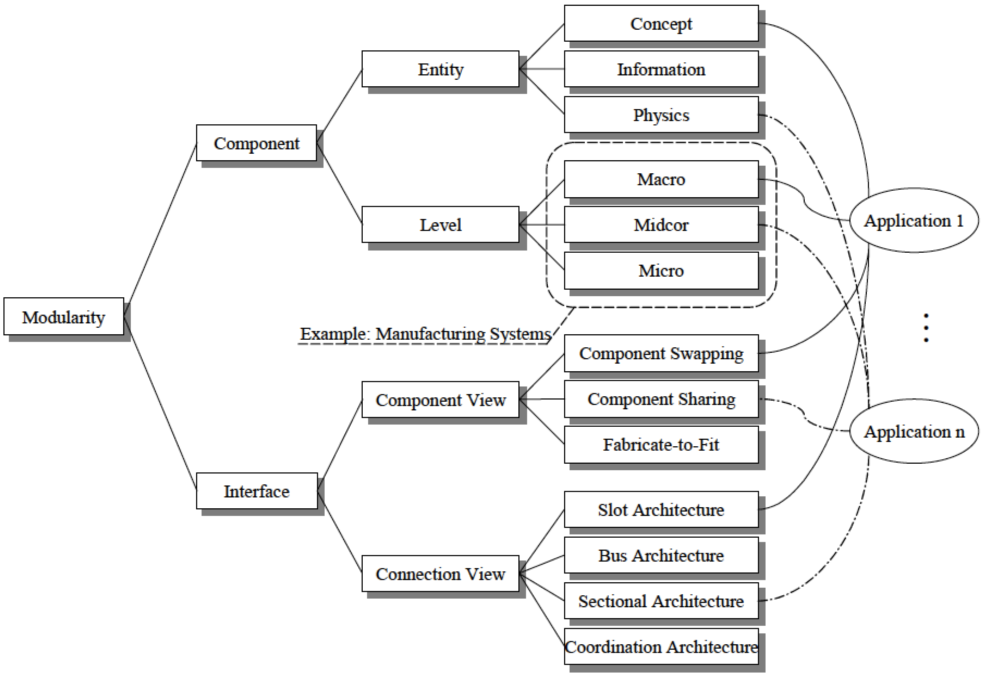

Figure 2-7: Representation of the taxonomy of modularity application, from [Bi and Zhang, 2001]

2.4.3 Stakeholders and Requirements

[Howarth and Hadfield, 2005] present a model for the stakeholders involved in sustainable product development (reference Figure 2-8). However, this is focussed on the stakeholders involved in requirements definition, rather than prototyping or production.

[Ali Khatami Firouzabadi et al., 2008] present another consideration of stakeholders within a decision-making environment, but this is again high-level and also generic in application and nature. Another generic approach is that reported by [Laporti et al., 2009] which is primarily concerned with requirements elicitation. This concept, in addition to the link to the stakeholders associated to products, is presented by [Macaulay, 1995] and highlights the benefits of collaborative requirements elicitation. Further to this, [Nilsson and Fagertröm, 2005] highlight the need to involve all of the stakeholders, manage their requirements and expectations and to ensure clear and consistent understanding between them. However, there is little real guidance in ensuring this happens [Vink et al., 2008]. There have been efforts towards the implementation of fuzzy logic to a stakeholder-oriented product conceptualisation model [Yan et al., 2009], but this is targeted towards the very earliest stages in product development and has no specific manufacturing considerations.

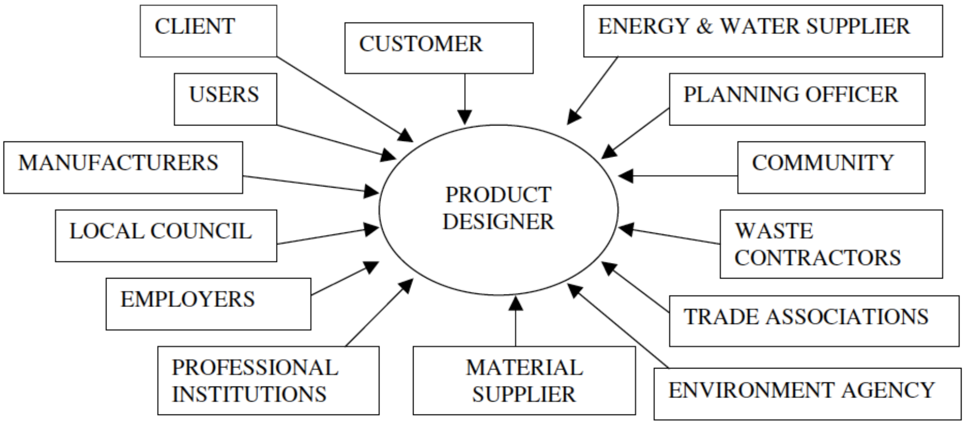

Figure 2-8: Typical stakeholders involved in product development, from [Howarth and Hadfield, 2005]

2.4.4 Capability Model

Capability models are used to evaluate what capabilities are required in order to produce the desired products. Capability models should be "tuned" for a specific application, such as [Matthews, 2006] which develops a capability model for improved process flexibility. It focuses on two "envelopes": capability and opportunity, shown in Figure 2-9.

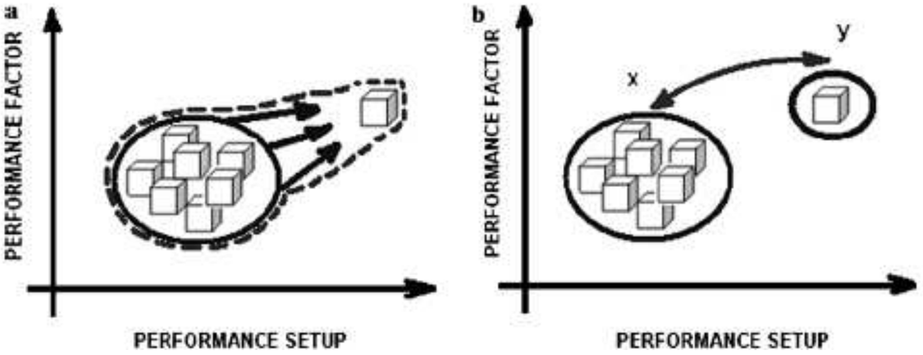

Figure 2-9: Representation of the setup envelope changes, from Matthews [2006]

Though not explicitly identified as Capability models, there has been other research into the identification of requirements for new or reconfigured assembly systems [Vos, 2001] and [De Lit and Delchambre, 2003] where methodologies and examples are given. This research does not focus on true reconfigurable, modular assembly systems and as such offer numerical interpretations of the existing human-centred design process. One exception to this is [Lohse, 2006], which specifically focuses on modular assembly systems. This work captures the requirements of a product, identifies the required processes and attributes equipment to those processes. The research is aimed at designing new assembly systems and so is missing the comparison element between required and available capabilities.

2.4.5 Cost and Performance Models

The consideration of cost is one of the most important when designing a system and in cases of high investment, such as assembly systems, the ability to accurately predict and control costs is a great advantage. Early work investigated applications such as stochastic optimisation, exemplified by [Tandiono and Gemmill, 1992]. Cost estimations can also be made based upon the activities within the manufacturing system in question [Özbayrak et al., 2004]. Further, [Amen, 2006] presents a cost-oriented line balancing model, which is based upon the simplified variant of the approach [Scholl and Becker, 2004]. There is a considerable focus in the literature towards costing of the product [Boons, 1998] based around the manufacturing system applied, but this does not include the specific variables inherent to manufacturing.

In addition to pure cost, the performance of a system is also highly dependant upon the assembly line balancing (ALB) conducted. [Boysen et al., 2007] present a review of the different tools and techniques available for consideration. [Defersha and Chen, 2006] provide a demonstration of the potential to use mathematical model to aid in the design of a cellular manufacturing system[1], the work also clarifies and supports the need to consider system design from an integrated and heuristic approach.

2.4.6 Critical Analysis

The literature reviewed in the preceding sections (2.4.1 to 2.4.5) has demonstrated a significant body of work, but is lacking in certain areas.

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[1] Cellular Manufacturing Systems are similar in concept to MMS, but with a greater focus on the premeditated delivery of a family of parts.

Ontologies and taxonomies have been presented linked to standard assembly systems as well as to MMSs. These are typically either high-level (workstation) or low-level (parametric) but do not focus at the equipment module level. As this is the level of granularity at which most RASs realise reconfiguration, it should be reflected in the associated taxonomy.

The consideration of the stakeholders associated with assembly systems is very limited: there are several stakeholder models, but these are comparatively high-level and generic. The primary benefit of a stakeholder model is that it defines and structures the roles of the people involved in the project. This can only be achieved with consideration of the specific nature of applications.

Additional models concerning capabilities and costs have also focussed on the use of either fully fixed bespoke systems or FMSs. This leaves a gap in the application of these models to RASs.

2.4.7 Summary

- There are a great number of ontologies and cost models for manufacturing and for assembly.
- There is a significant lack of specific consideration of either multiple products or of the micro domain.
- Several taxonomies exist, with potential to adapt to specific situations outside of those originally considered.
- The stakeholders involved in the delivery of assembly systems has been insufficiently modelled.
- There has been limited investigation into specification and design work based upon capabilities or with consideration of links to both products and processes.
- There are numerous cost models and line-balancing approaches, with significant success, but without explicit consideration of multiple configuration environments.

2.5 Conclusions and Key Gaps

The current state-of-the-art in manufacturing systems is that the majority of new lines are bespoke and single purpose. Generally, the system is designed to be as cost effective as possible, i.e. to achieve the required production criteria (such as parts per hour and failure rate) for the minimum cost and delivered in the shortest time. This pressure is driven by the market, which demands that products are available quickly and cheaply. As such, the manufacturers look to solve their immediate problems. [Du, et al., 2008, Daschenko, 2003, Smith, 2000]

There is, however, a growing awareness of the short-falls of this approach. Specifically, these are:

One purpose. This means that the system should be optimised for the original product. It also means that any changes to the product require substantial redesign and rework of the system – this is typically a slow and expensive process – so much so that systems are often scrapped and replaced rather than reconfigured.

Poor equipment re-use. As a result of the dedicated purpose of the system, the equipment itself is often so heavily integrated that reusing it within the next system is more expensive than starting over. This tends to result in premature scrapping of equipment.

Further to this, [Mital and Pennathur, 2004] highlight that the major drawbacks of standard, state-of-the-art assembly automation. The major issue highlighted is the **lack of flexibility**, backing this up with economic data (reference Figure 2-10) showing that the widespread introduction of automation has not resulted in an increase in productivity, but rather appears to have hampered it. Other economic factors are not discussed, but the trend occurs over a large timeframe, negating the effects of depressions etc.

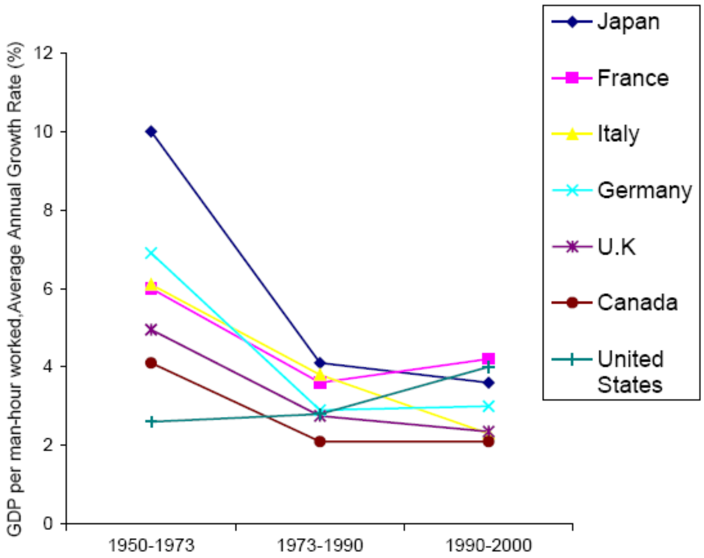

Figure 2-10: Productivity growth in relation to Manufacturing Automation, from [Mital and Pennathur, 2004]

It is clear that there is the need to develop *"an integrated modelling method in order to achieve effective and efficient modelling at the Cell level."* [Jin et al., 1995]

[Vos, 2001] has specifically highlighted that there is a clear need for the ability to **evaluate and compare system and product capabilities**. Such functionality could be scaleable to fit within product development phases and sufficiently abstract as to prevent prejudices from affecting the solution development.

2.5.1 Conclusions

The key conclusions which can be drawn from the literature are that, whilst research into System Reconfiguration has been ongoing for some time, the major efforts have focussed on tools and technologies that contribute towards the control - Reconfigurable systems provide huge challenges with respect to their control systems.

Design / planning for system reconfiguration. The work to date has been at a relatively high level, with the reconfiguration occurring at the workstation (or equivalent) level. There has been investigation into the design of flexible / modular assembly systems and, although there are some links to reconfiguration methodologies, it is mostly with regards to "from-scratch" designs. In these cases, existing equipment, architectures or multiple products are not considered and the design efforts have focussed on initial design of a new system and on the distribution of operations. Existing FMS are based upon the concept of linking a group of operations with one or more flexible robot(s) – the result is a rigid system with a wide range of capabilities that can be adapted to as many new products as possible.

2.5.2 Key Knowledge Gaps

The realisation of truly reconfigurable assembly systems is currently hindered by a number of issues. This thesis shall focus on three of these elements, which are judged to be significant in the realisation of RASs. These being:

- A coherent and unified model to identify and compare core functionality and to specify outline assembly system configurations with varying degrees of data.
- Simplification of requirements elicitation to account for multiple stakeholders, products and limited defined data.
- Configuration optimisation focussing on advantageous utilisation of core RAS functionality.
- Indicative projections of the impact of reconfiguration.
- Consideration of the micro domain and of high-value, low production products within RAS.

A Capability Model. This is the model that evaluates the existing system capabilities and the required capabilities for the new product/s, highlighting overlaps and gaps. This should also incorporate the customer requirements and offer some predictions of key performance indicators.

A Reconfiguration Methodology. This is essentially the procedure for completing the reconfiguration of the system; some will be common to all cases and some specific to each individual case. This takes account of issues not addressed in the capability model, such as logistics, health and safety, documentation and maintenance so that the system can be operated in an industrial environment.

Core Enabling Technologies. These encompass the specific needs of a modular reconfigurable system for micro assembly, developed in a collaborative and dynamic environment.

Additionally, these gaps can be further enhanced by specific consideration of focus on:

- Precision production and the micro domain,
- Assembly aspects of manufacturing, rather than machining,
- Multiple product Reconfiguration Scenarios,
- Staged evaluation, in-line with product development cycles,
- Reconfiguration of existing systems,
- Modular system framework and architecture.

3 Research Methodology

The literature review has shown that the implementation of modular and reconfigurable assembly systems requires that a number of challenges be overcome (reference Section 2.5). Furthermore, it has been outlined that the micro domain adds additional challenges with respect to the equipment required.

The objective of this chapter is to clarify and describe the overall research approach employed as well as the core principles behind the investigated methodology.

3.1 Description of the Research Methodology Utilised

Research is defined by [Svensson, 2003] as *"a mediator between reality and scientific knowledge"* and is often realised through cycles: research observes reality, which, in turn, influences the research. New scientific knowledge observes the research and is influenced by it.

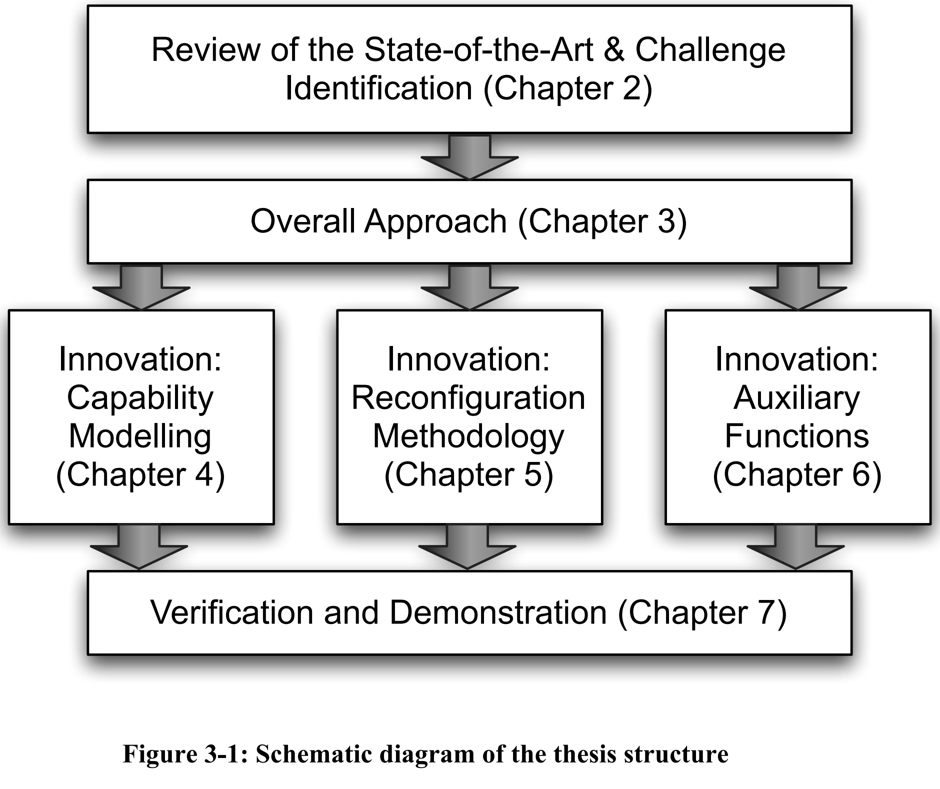

Figure 3-1: Schematic diagram of the thesis structure

In order to result in the creation of new scientific knowledge, this research should observe reality, but it must also follow a structured route. [Philips and

Pugh, 2005] define such a route in the form of four key theoretical areas that need to be addressed during the process of scientific research. These are; *Background Theory*, *Focal Theory*, *Data Theory* and *Contribution.* This thesis follows this overall research approach; the specific application of which is reflected schematically in Figure 3-1.

3.1.1 Research Objectives

The proposed methodology is intended to broadly follow the, currently human-centred, complex decision-making approach from the specification of requirements by the customer through to the specification and planning of the assembly system solution. The research objectives, as defined in Chapter1, are:

- To develop a new Capability Model to enable the identification, definition and comparison of capabilities.
- To formulate a Capability Taxonomy, which will provide a standard and structured definition of 'capability'.
- To propose a Reconfiguration Methodology to enable configurations to be evaluated, specified and validated.
- To develop a number of Auxiliary Functions that will support the overall approach.
- To Validate the developments and proposals through the utilisation of a number of test cases that are to be derived from research projects.

3.1.2 Focal Areas

The approach will, for the purposes of this research, focus on **assembly processes**, within the **micro domain** and reconfigurations of the **mechanical components** only. This will enable detailed development of the approach; further elements will be considered from a theoretical viewpoint and considered as a means of expanding the approach.

3.1.3 Assumptions

The priority for implementers of RASs is to first know if a new product can be produced on the system.

The implementers of any RAS need to be aware of the capabilities and implications of any proposed reconfigurations of the system. The first and most important decision is whether or not the reconfiguration is possible. If it is not, or at least not feasible within pre-defined parameters, then the project can be changed in focus away from reconfiguration of that particular system. Such a quick analysis function is likely to offer savings in cost and time spent investigating impossible or severely sub-optimal solutions.

The consideration of multiple products and their respective configurations will be advantageous, particularly in the high-value, low volume product area.

The greatest benefits of RASs will be realised in situations where reconfigurations are frequent occurrences. These cases are exemplified by producers of high-value, low volume products, which are often produced on lines with extensive use of manual operators to reduce reconfiguration costs.

There are currently insufficient enabling technologies for the RAS paradigm to be successfully implemented in the micro domain.

The literature review in Chapter 2 has shown that micro-assembly remains a great technical challenge. The realisation of highly specialised processes and equipment within a RAS is not currently achievable and it is necessary to evaluate how, and indeed if, this can be accomplished.

The use of pre-defined concepts, technologies and processes is essential for the approach to be realistic and reflective of industrial applications.

As far as is reasonable, the approach should utilise and integrate the existing effect concepts, technologies and processes. Through doing so, the approach will both be more realistic and have a greater potential for inclusion in industrial practises.

The operator of the approach will be a relevant expert. The approach itself is aimed at expert users, primarily experienced system integrators. This has an impact on the use of terminology and the expectation of a level of technical understanding, meaning that only the innovative elements of the approach be explained.

The necessary system architecture, both mechanical and control, is in existence and is operational. This thesis will investigate the applicability of certain technologies, but the approach itself will not aid in the design of an appropriate architecture.

3.2 Definitions and Requirements for Reconfigurable Assembly Systems

Understanding and evaluating the issues and gaps highlighted by the Literature Review (Chapter 2) is an important first step in the realisation of a solution. Within the context of this thesis, there are two main classes of requirements: *Methodology Requirements*, and *Assembly System Requirements*. The former covers the requirements that the methodology itself should deliver, the latter refers to the specific technical requirements for each assembly system. Assembly System requirements are covered in Chapter 4.

3.2.1 Requirements for the Proposed Approach

This section of the research focuses on the wider issue of the requirements for the approach itself.

- The approach must address the key gaps.
- The approach must meet the specific needs of each of the stakeholders.
- The approach must offer full upgradeability and customisability.
- The approach must facilitate the identification and comparison of multiple solutions.
- The approach must be integrate-able within existing industrial practises.

The approach described within this thesis addresses some of the key obstacles preventing successful multiple reconfigurations of modular manufacturing systems. These obstacles have been highlighted in Chapter 2 and clearly demonstrate the need for a unified and integrated approach. Furthermore, it has been demonstrated that integration to current practises and industrially implemented software will enhance the potential uptake of the solution. The integration of the approach must occur both within the approach itself (i.e. of the key innovations and their constituent elements) and of the approach to standard operational practises in order for it to be widely adopted.

3.3 Overview of the Proposed Approach

RASs are intended to provide the basis for a single assembly system that, with the integration of different equipment modules, can deliver a broad range of production functionality. [Pahl and Beitz, 1996] highlight that generally the success of a modular and/or reconfigurable system is dependant upon the applicability and relevance of the system architecture. It is thus important that any intended reconfiguration of the system be determined and evaluated as early in the design cycle as possible so that, should the architecture prove to be sub-optimal, allowances can be made. These may include adaptations to the processes or products, the implementation of production on a new or different system or even outsourcing of production. Whatever the outcome, the earlier it is defined the more efficiently the product can be delivered.

It is therefore important that a singular integrated methodology that can function with minimal initial data on products and requirements be developed. Such a methodology could then be used as a means of quick evaluation of any proposed reconfigurations to, at very least, determine if it is feasible or even possible to meet the needs outlined. Equally, this ‘quick-look’ should not be lost and replaced by more detailed evaluation, but rather built upon iteratively as the reconfiguration project itself builds and the available data increases. This will enable the methodology to not only function as an early analysis tool, in the same manner as DFMA, but also become a design tool itself.

The purpose of the assembly system design is to find a suitable solution for a given set of product based assembly requirements by selecting and configuring available equipment modules into an assembly system [Lohse, 2006]. Assembly system design comprises of a number of different stages that need to be accounted for in the methodology. The key phases are Definition and Analysis: the definition phase converts requirements derived from the products into the necessary processes and (where necessary) the architecture, the analysis phase performs validation and verification of the generated solution with respect to the initial requirements.

Therefore, the methodology is entitled the *Capability-based Approach for Multiple Assembly system Reconfigurations and Analysis*, or CAMARA. The subsequent sections describe the potential CAMARA applications as well as the overall processes involved.

3.3.1 Core Processes of the Proposed Approach

The proposed solution is to develop an approach that acquires and processes the relevant data and can offer a variety of solutions. The proposed approach follows a sequential route through a series of processes, represented by Figure 3-2. These processes are relatively generic and describe the necessary decisions that must be made in order for a viable single methodological approach to be realised. The core of the approach is to define these processes so that each can be developed and refined independently, without impacting the functionality of the others. These processes rely on an appropriately trained user to drive them – this may be, and is expected to be, an individual working within the System Integrator. Specifically, they are:

Process 1: Project Requirement Definition. The user defines the manufacturing project – this consists of details of the products, production timescales and other key factors such as budget or equipment constraints.

Process 2: Required Capabilities Definition. The project requirements are defined as Required Capabilities – this is done utilising the Capability Taxonomy. This produces a list of capabilities for each product.

Process 3: Available System Definition. The user defines the existing manufacturing system (if applicable) – this consists of details of the equipment only, the current role/purpose is not relevant to the analysis.

Process 4: Available Capabilities Definition. The available system equipment is defined as Available Capabilities – this is done utilising the Capability Taxonomy. This produces a list of capabilities for the existing system.

Process 5: Capability Comparison. The capability lists are compared to find commonalities and differences. The frequency of occurrence of each capability is logged and forms the basis for prioritisation. The output is a number of capability sets; one set for each product configuration and one overall minimised capability set that will deliver all of the products.

Process 6: Equipment Selection. Taking the capability sets, equipment modules are linked to each capability. The selection is based upon different criteria; these criteria are prioritised by the user, depending on the particular project requirements. These are crucial for defining the equipment allocation method. The outputs are equipment sets matching those of the capability sets.

Process 7: Equipment Validation. The equipment sets are validated to ensure that it is possible to actually deliver them with available equipment. This process will also identify the additional capabilities that each configuration may have as a result of imperfect equipment to capability matches.

Process 8: Configuration Optimisation. Using the validated configurations and capability sets the different configurations are optimised based upon the initial project requirements.

These 8 Processes broadly represent the objectives of the approach and what the user will do, but do not indicate solutions or the proportionate effort of the approach. For example, the requirements definition will be comparatively laborious for the user as they will need to enter various data, however the analysis that is performed will be performed within a software program and so be ‘invisible’ to the user.

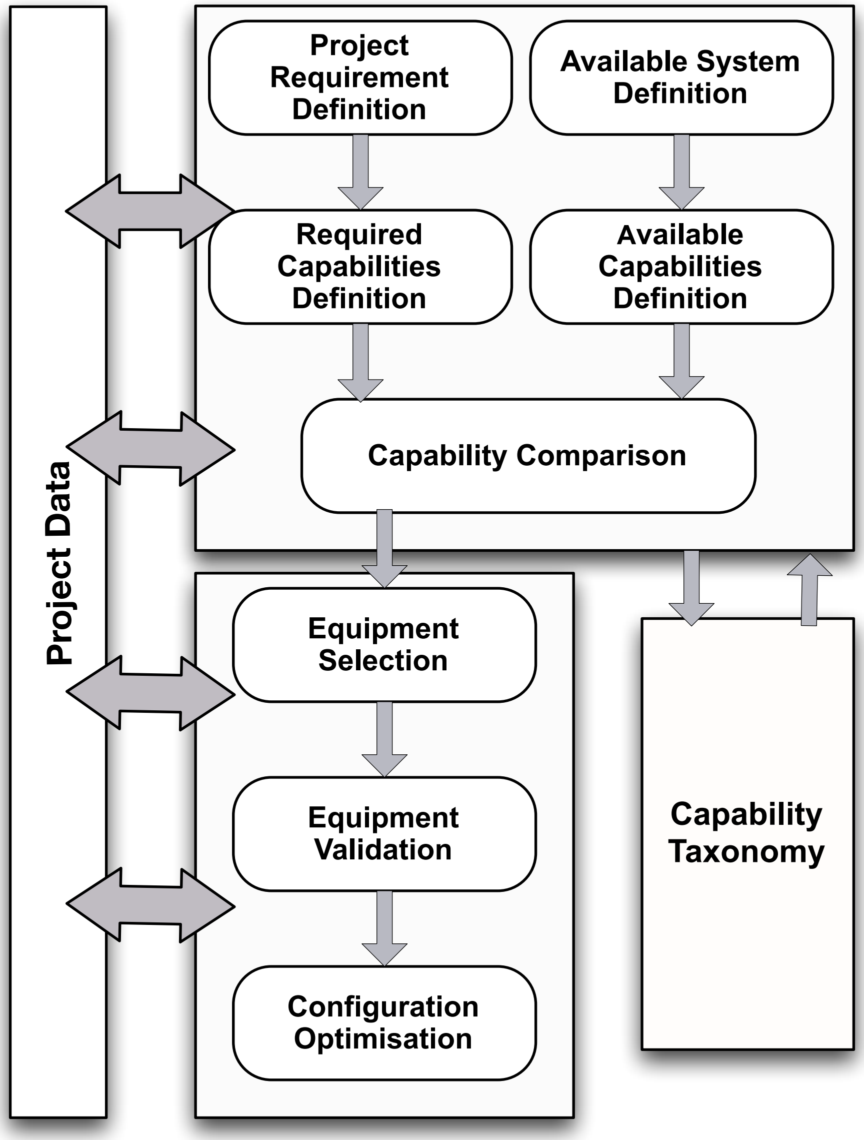

Figure 3-2: Overview of the proposed approach

3.4 Details of the Proposed Approach

The proposed CAMARA approach consists of 4 elements, shown in Figure 3-3, these are:

1. Capability Model
2. Reconfiguration Methodology
3. Enabling Technologies
4. Verification

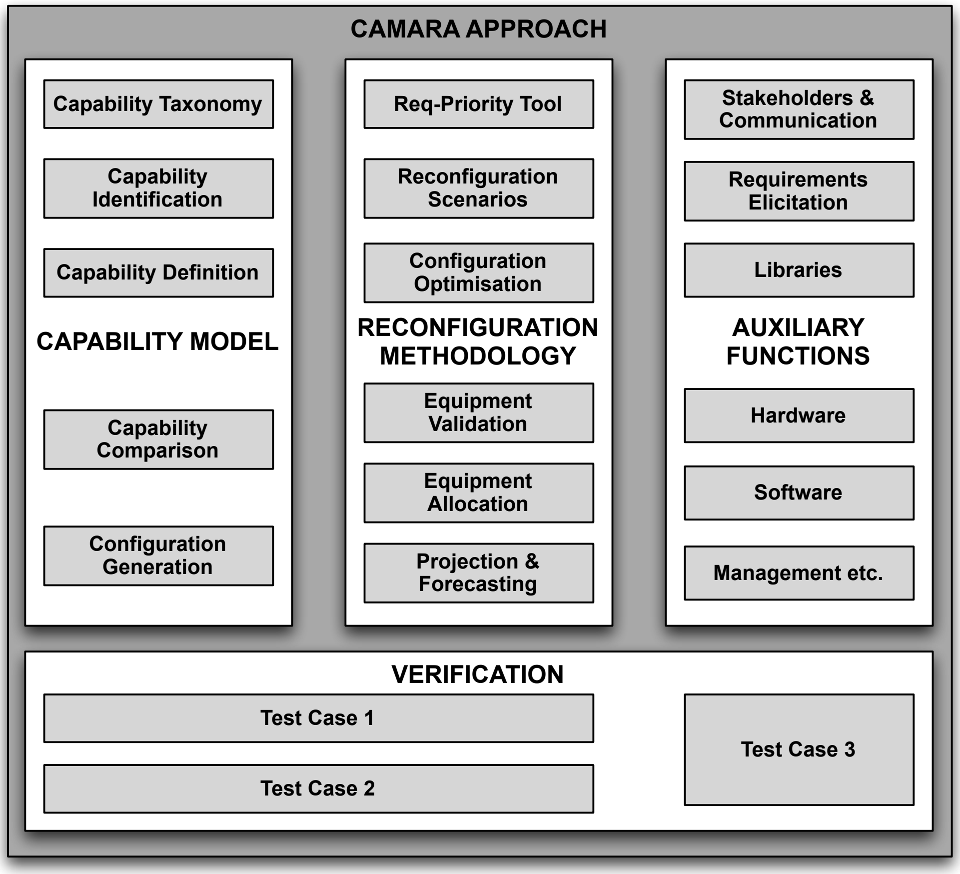

Figure 3-3: Overview of the proposed approach

3.4.1 Element 1 – Capability Model

The Capability Model works through the consideration of the abstract capability concept. The model will take the specified requirements and produce a series of capability sets that broadly define the required configurations. More specifically, the model will encompass:

- A Capability Taxonomy.
- Capability Identification
- Capability Definition
- Capability Comparison.
- Provisional Configuration Generation

The *Capability Taxonomy* will provide a description of the capability concept that is common and coherent to both products and processes. The taxonomy needs to be structured hierarchically so that at different stages in the product development, when different levels of information are known, the same taxonomy can be used. It is also important to note that, by keeping the *Capability Taxonomy* separate from the rest of the methodology, it is possible to update it to suit a particular purpose, industry or company.

The *Capability Identification* will enable the various stakeholders involved in the project to locate and identify the capabilities associated with both the required products and the available system/equipment.

The *Capability Definition* defines the capabilities associated with the products and the existing manufacturing system, it also defines the scenario in which the production will be occurring as well as storing this data in the relevant locations ready for the analysis in the later phases. The definition is dependant on the *Capability Taxonomy*.

The *Capability Comparison* provides analysis of the compatibility of capabilities and thus defines which of the required processes can be delivered by existing equipment and which require the procurement of additional equipment. At this stage, such analysis will only be provisional and provide what is possible. Further analysis will be required to identify the best solution for the application

The *Provisional Configuration Generation* focuses on performing analysis of the capabilities: after the comparison of the capabilities, the boundary configurations can be found to set the range in which any solutions will be defined.

3.4.2 Element 2 – Reconfiguration Methodology

The Reconfiguration Methodology provides a more detailed analysis and specification of the solution configurations such that a modular system can be realised. It comprises of the following:

- Requirement/Priority Analysis
- Reconfiguration Scenarios
- Configuration Optimisation and Validation
- Production Sequencing and Line Balancing
- System Specification

- Projection and Forecasting

The *Requirement/Priority Analysis* provides consideration of the priorities and specific requirements set out by the customer. The result is the indication of the likely nature of any solution and the possible suggestions for alteration of requirements/priorities to alter the outcome. This element is to be based largely on experience and lessons learned. The *Reconfiguration Scenarios* provide information that is essential to the decision-making throughout the methodology. Primarily defined through the previous *Requirement/Priority Analysis*, the appropriate scenario guides the strategies and decisions implemented in the methodology.

The *Configuration Optimisation and Validation* applies strategies in the generation of detailed configurations as well as validating that it is feasible with the available equipment modules. The *Production Sequencing and Line Balancing* provides the additional details necessary to order the reconfigurations and locate modules within the system. The *System Specification* is the clarification and confirmation of all of the relevant details associated with the proposed system that enable it to be realised. The *Projection and Forecasting* utilises the available information and the System Specification to project relevant performance indicators. This information may inform final changes or the acceptance of the solution and progression on to implementation.

3.4.3 Element 3 – Auxiliary Functions

The Enabling Technologies encompasses a number of different facets that combine to enable the deliver of the approach within a modular assembly environment. This includes: a Communication Architecture and Stakeholder Model, Equipment, Product and Solution Libraries and appropriate hardware and software.

3.4.4 Element 4 – Validation and Verification

In order for the conducted research to be properly assessed, it is necessary to define the means by which the approach and its requirements can be evaluated and verified. To this end it is important to define the key application scenario and the test cases.

3.5 Test Cases and Key Application Scenario

As outlined previously, the greatest beneficiary from the RAS paradigm are the producers of high-value, high-complexity, low volume products. This, in more specific terms, refers to products that, regardless of size or purpose, have a high manufacturing cost (expensive components, lengthy assembly times or a combination of the two), consist of a number of different components requiring 'complex' assembly processing and are produced in low volumes. The terms 'complex' and 'low volume' are somewhat subjective and dependant on the application. Generally, 'complex' refers to products that require assembly processes beyond the standard 2.5D pick and place operations (i.e. stacking of parts on top of and/or inside one-another). 'Low volume' can be encompassed as products produced in the order of hundreds *or* thousands, rather than hundreds *of* thousands and more.

One of the clear application areas is that of product development and prototyping. A major challenge faced by industry is the realisation of conceptual and one-off products into the marketplace without substantial financial risks. Traditionally, such activities are undertaken by Research and Development (R&D) facilities or divisions. However, cost-cutting and risk-aversion has resulted in many companies reducing their R&D commitments, at the very least expecting substantial risk reduction. This situation makes the transition through the Technology Readiness Levels (TRL) difficult.

An additional problem is that of production volume up-scaling. Generally, products are initially produced in very low volumes (prototypes, evaluation models) and this is gradually scaled-up towards full production volume to meet sales demands. Predicting the expected sales volumes is highly important when using bespoke, single purpose solutions as they cannot be (easily) altered at a later date. Over-predicting sales will result in an under-utilised system, resulting in greater production cost per unit, reduced profit margins and increased pay-back periods. Under-predicting sales can result in long customer waiting lists and missed market share. Both the FMS and RAS paradigms have been proposed as solutions to this challenge.

On a processing front, whilst prototypes and initial evaluation products can be made by any available means, in cases where official certification of trial batches is required, the production method used in delivering those batches should closely resemble that of the final mass production line. If the trial products are produced using other methods, the potential is that the final products will not perform in-line with the results of the trials.

An area in which all of these points apply is that of Medical Devices and as such this forms the basis for the core application scenario. Medical Devices are products that are manufactured and used in order to benefit human health. Miniaturisation and function integration has seen these devices becoming more prevalent and is leading to a new generation of swallowable, injectable and implantable devices for the diagnosing and treating of ailments.

3.5.1 Application Definition Process

During the course of this research, a number of workshops and interviews were conducted. These events, which were primarily performed within the context of the 3DM project, focussed on discussing the issues surrounding the delivery (i.e. design, manufacture and assembly) of microdevices. These events were:

- 20th November 2006: session to discuss the proposed test case products with the designers.
- 23rd January 2007: review of possible microtechnologies with project partners.
- 28th February 2007: session to discuss the proposed test case products with the designers and customers.
- 2nd May 2007: review of possible microtechnologies with project partners.
- 14th-15th June 2007: workshop event to discuss innovative solutions and overall production requirements from existing microdevice producers and customers.
- 20th September 2007: interview and discussion with microdevice customer.
- 29th-30th October 2007: workshops and discussions concerning production issues related to the test case products.

- 25th January 2008: evaluation of production techniques and tecnologies.
- 28th February 2008: discussion of proposed revisions and refinements to test case products and impact on production.
- 17th April 2008: discussion of key challenges and requirements with microdevice producer/customer.
- 15th May 2008: discussion of key challenges and requirements with microdevice producer/customer.
- 23rd-24th June 2008: workshops and discussions concerning production issues related to the test case products, involving project partners, device designers, producers and consumers.
- 1st-4th September 2008: several workshops and discussions with project partners on progress and impact of previous changes. Final selection and design freeze of key test cases.
- 23rd October 2008: meeting with key test case designer and customer to detail the requirements and specifications.
- 30th January 2009: final meeting with key test case designer and customer to detail the requirements and specifications.

All subsequent meetings between the partners were with regards to the discussion of progress in the work and the results themselves. The meetings and events listed above were fundamental to the development of the overall approach and methodology described in this thesis.

There were a number of parties involved at various stages in the events listed. They included the various 3DM project partners (Universities of Greenwich, Cranfield, Cambridge, Loughborough, Brunel), the academic and commercial test case product designers (NPL, Herriot Watt University), and the companies involved in the production of the devices (Astra Zeneca, Unilever, GlaxoSmithKline, Unipath, Epigem, BAE Systems, Carl Zeiss) as well as several companies and individuals who were consulted with their various expertise (TQC Ltd., Tecan, SPI Lasers, Sonics and Materials, Flomerics, Physica, Microstencil, DotDotFactory).

The findings formed a significant basis for the initial scoping of this work as well as supporting the decision-making associated with the individual elements of the approach. In summary of these events, in addition to the specific points concerning the test case products themselves, a number of general points were ascertained:

The micro domain poses significant challenges for processes that would be comparatively simple in the macro scale. All parties agreed that there is a significant processing gap between conventional industrially-based manufacturing and assembly technologies and those based in the laboratories, intended for prototyping and development.

RASs are currently employed only rarely, and never taken full advantage of. All of those directly involved in production and/or assembly were aware of the RAS paradigm, but few had experience of their implementation. The few, anecdotal, references to RASs indicated that they were implemented only for the reduced integration effort during initial installation.

Structured design approaches, specifically for systems delivering microdevices, are needed. Forecasts of systems, configurations and their impacts would greatly facilitate RAS implementation. By focussing on microdevices, and the technologies required to deliver them, significant benefits can be achieved for customers and designers. The provision of key information prior to the commitment of resources will be important for the justification of adopting RASs.

These overall points support the aims of this thesis and indicate that there is a clear commercial need for the proposed approach.

3.5.1.1 Impact on Approach

In addition to supporting the overall aim of the research, the information gathered during the events listed has aided in several key decisions made with respect to the proposed approach. These include:

- Development of the Capability Class structure (Section 4.2.1).
- Method for the selection and identification of Capabilities (Section 4.3.1).

- Consideration of boundary configurations for initial assessment (Section 4.3.3.2).
- Implementation of simplified requirements elicitation through Production Scenarios concept (Section 5.2).
- Simplification of Priority Scoring, using only integer values (Section 5.2.2.1).
- Development of the fictional products for Test Case 1 (Section 7.1)
- Selection of the products for Test Case 2 (Section 7.2).

In addition, it was commented that the axiomatic design principles were often utilised and the axioms themselves can be useful in the conceptual stages of design work.

3.5.2 Application Description

The application and scenario described is chosen as the basis for the presented research: whilst the approach itself is generalised to be applicable to as much of manufacturing as possible, the specifities needed to explore deeper into the concepts are made with this application in mind.

Company X designs and produces miniature and micro medical devices for various diagnostic and treatment solutions. Their current situation is:

- *They have several operational lines producing products with no current issues or foreseeable changes.*
- *They operate one modular and reconfigurable assembly line. The product on this line is due to be discontinued in the immediate future.*
- *They have preliminary designs for six new products, including one that is a departure from their traditional area.*
- *Each of these products is due to be put through clinical trials before full production can commence.*
- *The trials are all due to start simultaneously to minimise the time-to-market.*
- *Only one line is going to be used to produce the batches to reduce the financial costs.*

3.5.3 Summary of CAMARA

The CAMARA Tool enables the production of the System Configuration Lifecycle through the application of a series of structured phases, which are represented in Figure 3-4. These phases are drawn from the original specification of the proposed methodology, and can be divided into a number of steps, shown in Table 3-1.

Table 3-1: Summary of CAMARA phases and steps

Phase	**Step**
Requirements Elicitation	Define the stakeholders
	Define the existing system
	Define the products
	Define requirements and priorities
	Assess requirements and priorities
Capability Identification	Identify required capabilities
	Identify available capabilities
Capability Definition	Define required capabilities
	Define available capabilities
Capability Comparison	Compare available and required capabilities
	Identify the three capability lists
	Generate the boundary configurations
Configuration Selection	Evaluate configurations against requirements
	Select most appropriate configuration type
Configuration Analysis	Apply reconfiguration strategy
	Update each configuration
Configuration Validation	Validate each configuration against requirements
	Validate each configuration against equipment
Total System Validation	Validate total system against requirements
	Validate total system against equipment
Production Sequence Analysis	Compare configurations
	Identify optimal configuration sequence
Equipment Module Allocation	Allocate modules based on requirements and priorities
	Generate System configuration lifecycle

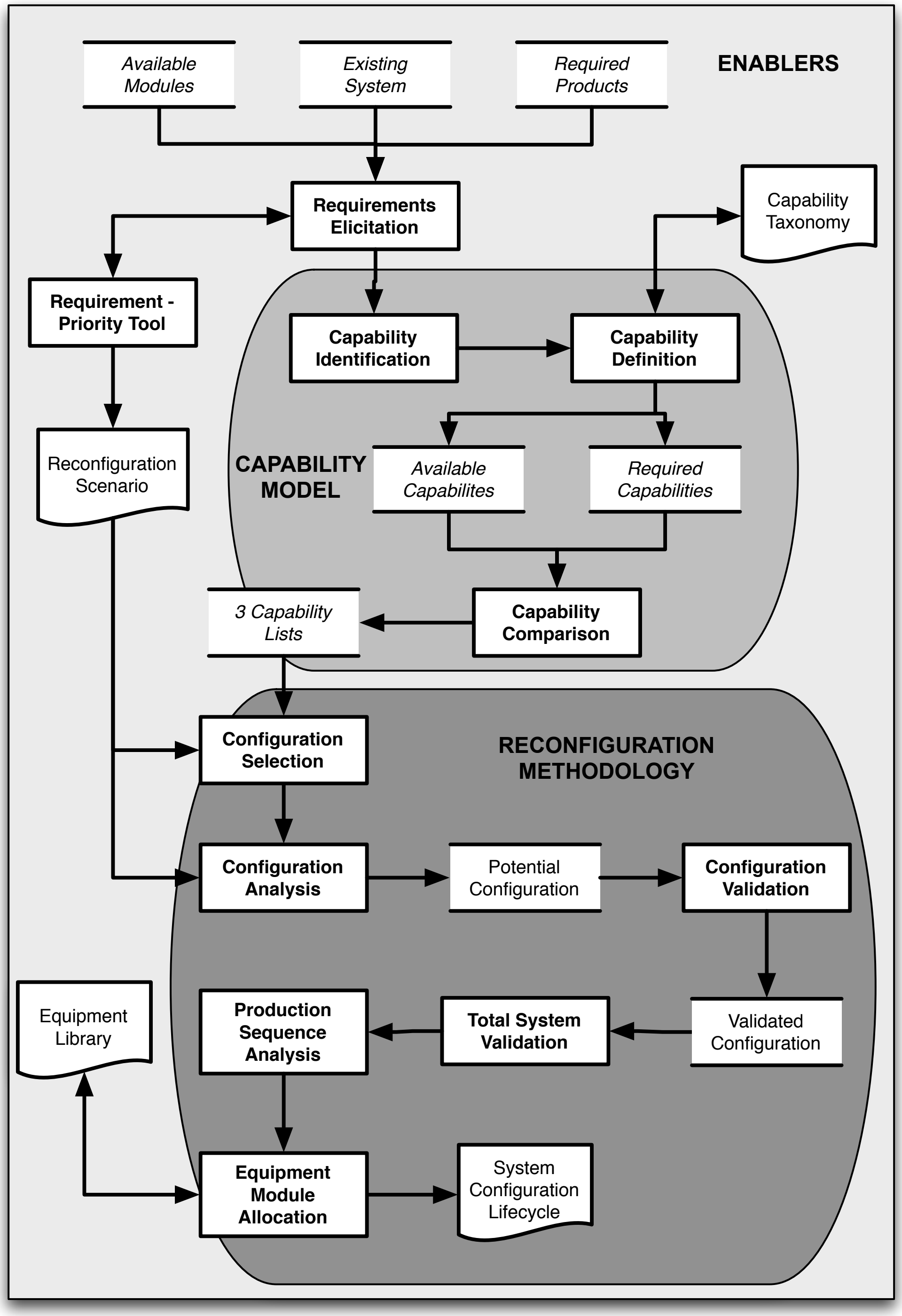

Figure 3-4: Summary of the CAMARA steps

4 Capability Model for the Evaluation of the Required Products and Available System

Chapter 2 identified the key challenges preventing the realisation of RAS in a multi-product, multi-configuration scenario. Chapter 3 outlined the CAMARA approach that aims to address these challenges, the first main element of which is the Capability Model. This chapter describes in detail the proposed Capability model.

The proposed Capability Model combines the roles of Processes 1 to 5 as outlined in Section 3.3.1. It has a strong relationship to the Capability Taxonomy, and hence the taxonomy is described in this Chapter, but this does require that changes made in one be reflected in the other, provided the core structure of the *Six Capability Classes* is maintained.

Capability models are used to quantify and structure decisions traditionally made by a team of engineers (system integrators). A common approach is to try to directly convert the (very iterative and human) design process into one which can be performed autonomously by a software program. The major issues with this, relating to reconfigurable systems, is that the process is heavily reliant upon experience and thus requires vast amounts of data to be input and stored in libraries so that the program has a “memory” of past projects. Furthermore, there are a huge number of variables with complex interactions, often these are not fully known, quantifiable or predictable.

The proposed Capability Model, which is outlined in Section 4.1.1, therefore looks at a different solution. The user drives the model; the user is anticipated to be either the customer or the system integrator. An important preliminary stage to the model is that of project requirements definition; this is not explicitly part of the Capability Model and are covered fully in Section 5.1.2. These requirements are defined within four key areas: *Product, Equipment, Environment* and *Priorities*. This Chapter presents and discusses the theory of the model.

4.1 Introduction

A Capability Model is a means of representing data and information without a focus on the physical manifestations. This is an important aspect of solution generation as it isolates the decision from potential preconceptions. The human process of finding solutions to problems is very often affected by the consideration of ‘similar’ problems and solutions encountered previously. Thus, the focus on the core principles of the problem and solutions has the potential to find the optimal, rather than previously experienced, result.

The key aim of this model is to identify and define the *Available Capabilities* and the *Required Capabilities*, to compare them and utilise the results to generate some provisional configurations. These capabilities are divided into *Capability Sets*. The outputs from the model are the *Three Capability Lists* for each product/configuration and the *Boundary Configurations*, which form the primary input for the Reconfiguration Methodology (described in Chapter 5).

The *Available Capabilities* is derived from the equipment modules and are, for the purposes of this model, the capabilities that are provided by the system and equipment that currently exist and will be available for the reconfiguration. One of the key innovations of this model is that the system and equipment available to the manufacturer is considered separately from equipment modules that will be procured.

The *Required Capabilities* are those that must be delivered in order for each product to be assembled. This does not refer to the capability *of the product* but rather the capabilities *that are required of a system* in order for that product to be delivered. This is an important distinction to make. It is also important to retain the capabilities in separate sets.

Capability Sets are groups of defined or undefined capabilities. Within this approach, the primary reason for grouping capabilities is that each product is produced by a different configuration (it may be that in some cases products are produced by identical configurations, but this is anticipated to be the exception rather than the rule). Each product and each configuration will be evaluated, in the first stages of the CAMARA approach, independently of the others. The *Capability Sets* are named with respect to the specific product or configuration they represent. In the case of the *Available Capabilities*, there is likely to be only a single set, but this chapter also describes the potential expansion of the model to identify the most suitable line to produce each product, in which case multiple *Available Sets* may be compared against multiple *Required Sets*.

The *Capability Lists* are the main output from the Capability Model. Three lists are produced from the Capability Comparison process, which are each sub-divided with respect to the Required Sets. These lists are the *Surplus Capabilities*, the *Procure Capabilities* and the *Compatible Capabilities*, which form the first stage of configuration analysis. The *Surplus Capabilities* are defined as those Available Capabilities that have no use in the delivery of any of the required products and so are surplus to requirements. The *Procure Capabilities* are those Required Capabilities that the existing equipment cannot deliver and therefore must be procured for the system to deliver the product. Finally, the *Compatible Capabilities* are those capabilities that 'match'; i.e. there is at least the potential that the Existing Capability can deliver the Required Capability. The full details of the capability compatibility are described in Section 4.3.3.

The CAMARA tool is aimed at the micro domain. However, the Capability Model described in this chapter is, for the most part, independent of scale and so can be applied to any domain. The reason for this is the use of a separate *Capability Taxonomy* (reference Section 4.2), which isolates the specific technical aspects from the rest of the model.

4.1.1 Capability Model Overview

The core functionality offered by the Capability Model is the identification, definition and comparison of the required and available capabilities. To deliver this, the Capability Model is divided into a number of separate processes/phases. The key elements of the Capability Model are: *Capability Identification, Capability Definition, Capability Comparison* and *Capability Evaluation*. In addition, the model incorporates the *Capability Taxonomy*.

The first step in the model is *Capability Identification*. Capabilities are an abstract expression of the skills possessed by equipment and required by products. Therefore, it is necessary to implement a tool that guides the user in the recognition of the capabilities associated with either equipment modules or proposed products. Once the capabilities have been identified, the next step is that of *Capability Definition*. Each identified capability must be defined so that it can be properly analysed. The definition itself is relatively simple, once the appropriate taxonomy has been generated. The *Capability Taxonomy* is a hierarchical representation that aims to encompass all of the functionality within assembly. By sequentially defining individual characteristics, the exact definition for the capability can be derived. This can be numerically denominated, making further analysis simpler. This analysis is, at first, in the form of *Capability Comparison*, which consists of the division of the capabilities into their sets and then the determination of whether or not each capability matches any of the others. Finally, after the comparison, is the *Capability Evaluation*, which generates the *Capability Lists*.

4.2 Definition of the Structured Capability Taxonomy

Although not directly a part of the Capability Model, the influence and importance of the Capability Taxonomy is particularly high. The model is structured only around the use of the six Capability Classes, thus any taxonomy that follows the same structure can be compatible with the model. Furthermore, as the capability definitions are drawn from the taxonomy, the quality of the analysis and the results is dependant on the accuracy and applicability of the taxonomy.

The Capability Taxonomy is based upon operator-oriented definition, thereby utilising existing knowledge and expertise. It delivers a numerical output for comparison and so can be adapted to suit particular industries without affecting the methodology. Furthermore, the taxonomy has several tiers of detail designed to synchronise with the levels of data available at various product design and planning stages. This is an essential feature in maximising the potential industrial uptake and enables the methodology to be integrated as a Design For Manufacture and Assembly (DFMA) tool. The definition is such that, when described, a capability is equally applicable to Equipment and to Products.

The hierarchy shown in Figure 4-1 provides a good representation of a common assembly process classification. However, the transition from “Processes” to “Operations” assumes that the relevant equipment is implemented. For example, screwing cannot be delivered by the simple rotation of any equipment – there must be allowances for the resulting linear motion, the rpm usually must be high and there is often the need to control the torque applied. The proposed taxonomy does not imply a specific equipment-oriented solution by its definition; instead it is defined with respect to the functional requirements of the manufacturing process.

In order to facilitate the comparison, and in particular the configuration generation, it is necessary to ensure that **each module has one capability only**. The exception to this is that a combination or grouping of modules may offer additional capabilities; these are referred to as *'emergent capabilities'* and are far more complex to identify. Indeed, it is anticipated that only during operation, or through highly sophisticated simulation, will these become clear.

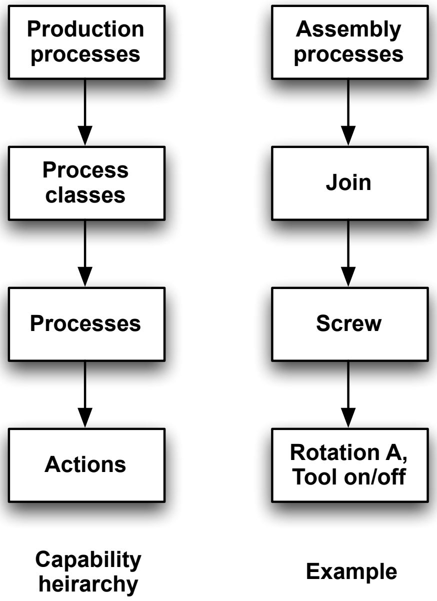

Figure 4-1: Example of the capability definition

In addition, it is an important feature of this taxonomy that it can be used at various stages in the product design cycle and therefore must have optional levels of detail. By working with the lowest level of detail, the absolute accuracy of the analysis is likely to be reduced, however it is hypothesised that the relative accuracy (i.e. when comparing different solutions) will not be impacted and thus give a good indication of the direction to take.

It is important to note that the quality of the results from this analysis are intrinsically linked to the quality of the definition process, and thus to the quality of the Taxonomy used. This means that it is necessary to ensure a highly suitable taxonomy is available and that it is used correctly for good quality analysis. However, it also offers the potential to use a tiered approach to the analysis – by acknowledging that there is limited information available, it would be possible to use a simplified taxonomy to i) accelerate the analysis process, and ii) to give some preliminary results based on early product design ideas. In this way it is possible to consider the analysis as a DFMA tool.

4.2.1 Taxonomy Structure: the Six Capability Classes

The derivation of the Capability Classes is based upon work by [Vos, 2001] and [Lohse, 2006] who proposed that the assembly capabilities be grouped into classes. However, the classes proposed in this thesis have altered in accordance with the shift in purpose. The Capability Classes discussed in this thesis are created primarily to enable the comparison and understanding of overall requirements and availabilities – for this reason direction of action (i.e. ‘gripping’ and ‘releasing’ as separate classes, as used by [Vos, 2001]) is not necessary. The intention is to not influence the solution found through the manner in which the data is presented. For this reason the Capability Classes may be considered abstract, using ‘Retain’ instead of ‘Grip’ and ‘Fixture’.

These six classes have been determined through an iterative evaluation of the overall impact of different structures. The primary aims of the use of capabilities are i) to ensure that the definition produced does not prejudice the solutions and ii) to enable effective definition from both equipment and product perspectives.

Test Case 1, described in detail in Section 7.1, was central to this work. The simplified products facilitated identification of appropriate equipment to delivery their assembly. Thus it was possible to evaluate and refine different potential class structures such that the same result would be obtained when identification was conducted from both the equipment and from the products.

A key decision made was that, in order to maintain a product focus, the capabilities should be actioned upon the product components. Equally, in order to ensure equipment relevance, the capabilities were also designed to be easily associated with and equipment module.

The six classes used have been identified as a basic decomposition of the actions imparted upon products by equipment. For the purposes of selecting and comparing equipment; directional terms, such as “grip” and “release”, terms that imply a solution, such as “insert” or “weld”, or terms that encompass the use of several equipment modules, such as “pick and place” are all counter-productive. Therefore, a more generalised class structure is implemented. The individual taxonomy implemented enables the detailed definition of the specifics of each capability.

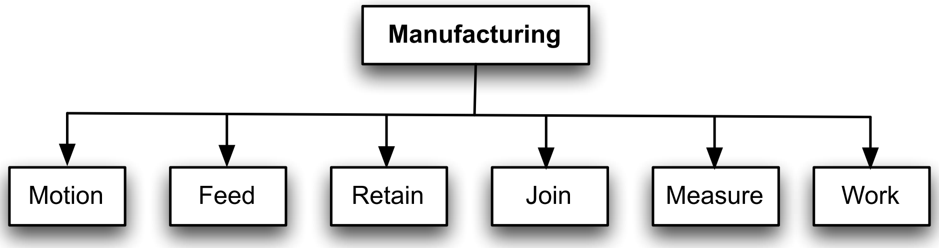

Figure 4-2: The top tier of the Capability Taxonomy - the Capability Classes

As outlined above, there are six *Capability Classes* that are representative of the majority of processes associated with manufacturing and assembly. At this stage it is important not to be too prescriptive (i.e. stating parts must be welded) as this could potentially block suitable solutions that may not be traditionally considered. Figure 4-2 illustrates the taxonomy hierarchy to the first two levels.

1. MOTION is the movement of one part/component with respect to the 0,0,0 point in the system. It can be described by factors such as: Position, Orientation, Tolerance, Range.

2. JOIN is the connection of two components, after which they are considered one part. This can be described by: *Reversible or Irreversible, Material (metallic, polymer, other), Tolerances, Performance (of joint).*

3. RETAIN is the maintaining of a component’s position and orientation relative to another point in the system (that point could be the 0,0,0 of the

system or the end of a robots arm). It can be described by: *Tolerance, Grip or Fixture, Product Properties*.

4. MEASURE is the quantification of either a *geometry, characteristic or performance factor of the component.* This is yet to be full investigated.

5. FEED is bringing components into the system from the external environment. It can be described by: *Delivery Method, Product Properties.*

6. WORK describes other processes, such as machining, that are not otherwise considered. This is included in the taxonomy for completeness, but is not to be considered until later in the research.

4.2.2 General Assembly Taxonomy Details

The main purpose of the Taxonomy is to enable the definition of the Capabilities in terminology that is common to both equipment suppliers and product manufacturers. It is also intended not to be prescriptive as to the solution. Crucially, it is also intended that the definition is flexible. The definition from the equipment side will generally be straightforward and involve known figures; the equipment manufacturers will already know the exact range, precision etc of the module concerned and so can enter the exact values. However, the product manufacturers may wish to consult the Methodology in advance of the final product designs being completed (indeed, it is the intention that the CAMARA tool can become part of DFMA procedures). Therefore it is necessary to include ranges of values represented by linguistic denominators (such as High, Medium and Low) that can be entered in the place of specific numerical input for criteria such as ‘resolution’ or ‘distance’. It is the values of these ranges which could be altered to suit individual users or applications. However, provided the Methodology is aware of these values then an appropriate and correct comparison can still be made later in the process. Figure 4-3 shows a short branch of the taxonomy to illustrate this point.

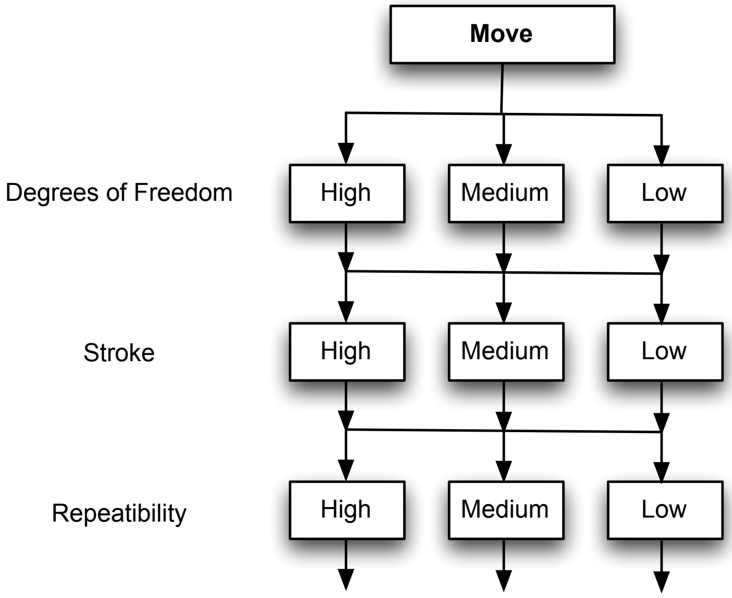

Figure 4-3: Illustration of a short branch of the Capability Taxonomy

The Taxonomy is structured hierarchically and can be viewed as an information flow diagram. However, it has been defined in full in a tabulated format as this enables it to be used as a manual tool and also allows for relatively easy upgrading to a piece of software that guides the user at a later point in the research. Whilst the taxonomy follows a tree structure, subsequent to the first two tiers the decisions made do not affect the route; the questions that follow are unaffected by the preceding answer. The difference is only in the final definition of the capability. The full Taxonomy is not included in this Chapter for conciseness, but is expanded in Appendix A. One important aspect of this taxonomy is that of the definition of the DoF: in order to uniquely define all possible combinations of the six possible DoFs within two digits, the characteristic is the sum of the values for each of them. By giving each DoF a numerical value double that of the preceding DoF, the numbers 1 to 63 represent the options. This is shown in Appendix A.

It should be reiterated that the Taxonomy is independent from the Reconfiguration Methodology – whilst it is essential to have a Taxonomy to perform the analysis, it does not have to be the particular Taxonomy presented here. Indeed, one of the primary benefits of the structure of the CAMARA approach is that any number of different taxonomies could be created for different applications and industrial sectors.

4.2.3 Micro Assembly Taxonomy Details

The micro domain, as described in Sections 2.2.1.4 and 2.3.1.2, provides additional complexity over the more conventional macro-scale. These points must be accounted for within the taxonomy in order for the CAMARA approach to deliver appropriate results. This specific iteration of the generalised taxonomy enables the CAMARA users to focus specifically on the micro domain and the common processes associated with it.

The Micro Assembly Capability Taxonomy, presented in Figure 4-4, is built upon the work of [Tietje, 2009]. The major differences are:

- Division of ‘Handling’ into ‘retain’ and ‘move’
- Nominal inclusion of the ‘measure’ and ‘work’ classes
- Use of linguistic variables
- Application to product definition as well as processes

The taxonomy continues to utilise linguistic variables rather than finite numerical values in order to make it a) easier to use at early product conception/development stages and b) faster and more intuitive to input data.

The six Capability Classes remain the same (as required by the Capability Model structure) and the same broad terms and principles apply, with certain significant changes to accommodate the micro domain. Issues such as modularity, control and equipment dimensions are covered by the consideration of the architecture itself. At this capability-oriented stage such equipment specifities are not considered, they are covered in the equipment validation.

The main aim is to assess and evaluate the core technical issues linked to the products and processes and not to consider specific solutions that may unnecessarily restrict the options presented or considered. There are numerous other factors, such as durability, ductility, operational temperature which are not included in this particular taxonomy as it is intended for use relatively early in the production design cycle. Such considerations should be part of a detailed taxonomy for full and final design work.

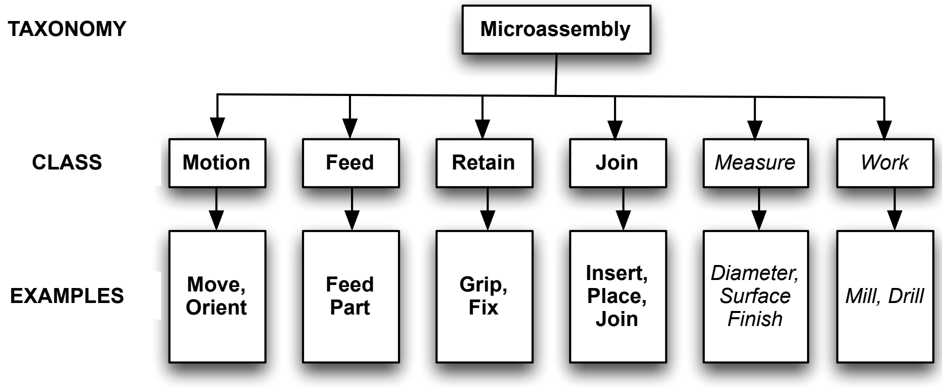

Figure 4-4: Overview of the Micro Assembly Capability Taxonomy

4.2.3.1 Move Micro Class

Generally, within micro assembly, the motion is required to be very precise in order for the micro components/features to meet.

Table 4-1: Overview of Move class of the Micro Assembly Taxonomy

Move Class			
Characteristic	**Unit**	**Product Indicator**	**Process Indicator**
DoF	n/a	Orientation complexity	Axes of motion
Stroke	mm	System layout/architecture (distance between pick and place positions)	Motion range
Repeatibility	nm	Connection to be made	System accuracy
Payload	g	Part mass	Maximum payload
Speed	mm/s	Cycle time requirement	System speed
Fragility	n/a	Part structure, material and features	System acceleration
Clean room compatible?	n/a	Clean environment required	Functions in a clean room
Vacuum compatible?	n/a	Vacuum required	Functions in a vacuum

Table 4-1 provides an overview of the key characteristics associated with motion in the micro domain and the associated factors that determine this from both the product and process perspectives. This can be used to define the detailed useable taxonomy. This leads to the production of the list of questions that can be posed for the definition of the capabilities (covered fully in Section 4.3.2). The generation of the questions is based upon the controlling factors for each characteristic as well as ensuring that the answers (High, Medium or

Low) match up. This is shown in Table 4-2, which identifies the relevant questions to be asked

Some of the Characteristics are more straight-forwards than others. For example; ‘Fragility’ is a complex concept but one that can be relatively easily assessed by a person, however the controlling factor with regards to the motion systems is whether the part will be damaged. As damage occurs mainly during acceleration (or deceleration) this is the key factor considered.

Whilst ‘Payload’ is included in this element of the Taxonomy, it is anticipated that almost all motion systems will have significantly higher payload limits than the mass of the relevant parts. This characteristic is more likely to be relevant to Retaining, however innovative motion approaches may have particularly low payload limits.

Table 4-2: Product and Process based questions for definition of Move class capabilities for the Micro Capability Taxonomy

Move Class			
Characteristic	**Options**	**Product Question**	**Process Question**
DoF	L, M, H	How many DoFs must product be moved through to complete motion?	How many DoFs does the module enable the product to move through?
Stroke	L, M, H	What is the distance between pick and place positions?	What range of motion can the module move the part across?
Repeatibility	L, M, H	What is the accuracy of the connection to be made?	What is the system repeatibility?
Payload	L, M, H	What is the part mass?	What is the maximum system payload?
Speed	L, M, H	What is the required product output rate?	What is the maximum system velocity?
Fragility	L, M, H	How fragile is the part?	How controllable is the system acceleration?
Clean room compatible?	Y, N	Is a clean room environment required?	Can the system function in a clean room?
Vacuum compatible?	Y, N	Is a vacuum required?	Can the system function in a vacuum?

4.2.3.2 Retain Micro Class

One of the key aspects of microassembly is the gripping and fixturing of parts. These are grouped as retention capabilities within this taxonomy.

Table 4-3: Overview of Retain class of the Micro Assembly Taxonomy

Retain Class			
Characteristic	**Unit**	**Product Indicator**	**Process Indicator**
Part Shape	n/a	Approximate part shape	Retainable shape
Part Size	μm^2	Maximum part dimension	Retainable dimension
Stroke	mm	Dimension between part gripping surfaces	Dimension between module gripping surfaces
Repeatibility	nm	Connection to be made	System accuracy
Payload	g	Part mass	System payload
Speed	s	Cycle time requirement	Gripping/releasing speed
Fragility	n/a	Part structure, material and features	Gripping force applied
Clean room compatible?	n/a	Clean environment required	Functions in a clean room
Vacuum compatible?	n/a	Vacuum required	Functions in a vacuum

Table 4-4: Product and Process based questions for definition of Retain class capabilities for the Micro Capability Taxonomy

Retain Class			
Characteristic	**Options**	**Product Question**	**Process Question**
Part Shape	P, B, D, Cy, Cx	What approximate profile / shape is the part?	What profile / shape part can be retained?
Part Size	L, M, H	What is the largest part dimension?	What size part can be retained?
Stroke	L, M, H	Distance between gripping positions?	Distance between gripping surfaces?
Repeatibility	L, M, H	What is the accuracy of the connection?	What is the system repeatibility?
Payload	L, M, H	What is the part mass?	What is the maximum module payload?
Speed	L, M, H	What is the required product output rate?	What is the maximum gripping/releasing time?
Fragility	L, M, H	How fragile is the part?	How controllable is the gripping force?
Clean room compatible?	Y, N	Is a clean room environment required?	Can the system function in a clean room?
Vacuum compatible?	Y, N	Is a vacuum required?	Can the system function in a vacuum?

Table 4-3 highlights that most of the characteristics in question in this class are the same as for the Move class, the only differences being the indicating factor that controls them. Degrees of freedom are not specifically considered as they are covered by the Motion capabilities. Table 4-4 provides the product and process oriented questions for the Retain class.

4.2.3.3 Join Micro Class

Within microassembly, joining processes are generally quite limited with respect to those available for industrial application. The selection of a process requires a greater degree of technical information than the Move, Retain or Feed classes. As a result, more characteristics are listed, but it is likely that at the early stages of product development, not all of the information will have been defined.

There are a number of factors that affect the details of the application of a process, such as the joint shape, type, angle etc. but these do not necessarily affect the initial selection of a process. Table 4-5 provides an overview of the characteristics and their associated indicators for the Feed class. Table 4-6 shows the questions, from both the product and process perspectives that enable the capability to be defined by the user.

Table 4-5: Overview of Join class of the Micro Assembly Taxonomy

Join Class			
Characteristic	**Unit**	**Product Indicator**	**Process Indicator**
Reversibility	n/a	Need to disassemble (without damage)	Ability to disassemble (without damage)
Repeatibility	nm	Accuracy of post-joining assembly	Accuracy of post-joining assembly
Joint strength	mN	Strength of joint	Strength of joint
Speed	mm/s	Cycle time requirement	Speed of processing
Medium	n/a	Possibility to use an additional part/substance	Joining mechanism/principle
Thermal process	n/a	Possibility to use a thermal process (without damage)	Joining mechanism/principle
Conductivity	n/a	Possibility to use electrical process	Joining mechanism/principle
Clean room compatible?	n/a	Clean environment required	Functions in a clean room
Vacuum compatible?	n/a	Vacuum required	Functions in a vacuum

Table 4-6: Product and Process based questions for definition of Join class capabilities for the Micro Capability Taxonomy

Join Class			
Characteristic	**Options**	**Product Question**	**Process Question**
Reversibility	Y, N	Does the joint need to disassembled without damage?	Can the joint be disassembled without damage?
Repeatibility	L, M, H	What is the accuracy of post-joining assembly	What is the accuracy of post-joining assembly
Joint strength	L, M, H	What is the strength of joint	What is the strength of joint
Speed	L, M, H	What is the cycle time requirement	What is the speed of processing
Medium	Y, N	Is it possible to use an additional part / substance?	Does the joining mechanism / principle use an additional part / substance?
Thermal process	Y, N	Is it possible to use a thermal process without damage?	Does the joining mechanism / principle use a thermal process?
Conductivity	Y, N	Is it possible to use an electrical process?	Does the joining mechanism / principle use an electrical process?
Clean room compatible?	Y, N	Is a clean room environment required?	Can the system function in a clean room?
Vacuum compatible?	Y, N	Is a vacuum required?	Can the system function in a vacuum?

4.2.3.4 Feed Micro Class

The Feed class offers particular complexities in the consideration of the orientation of the parts. Strictly speaking, this is a motion operation, but by giving feeders a separate Move capability, it would be difficult to ensure that they are not assigned to true motion operations. Therefore orientation is considered as an intrinsic part of feeding.

Furthermore, the method by which the parts are delivered greatly restricts the possible options for feeding types. Potentially, a solution is defined before the process has begun due to this. This work assumes that, whilst the parts have been defined, the delivery method has not. Repeatibility is in fact linked to the selection of other modules, particularly the grippers and motion systems.

Table 4-7: Overview of Feed class of the Micro Assembly Taxonomy

Feed Class			
Characteristic	**Unit**	**Product Indicator**	**Process Indicator**
Part Shape	n/a	Approximate part shape	Feedable shape
Part Size	μm^2	Maximum part dimension	Feedable dimension
Orientation	n/a	Rotational axis orientation required	Possible rotational axis orientation
Fragility	n/a	Part structure, material and features	Feeding / orientation mechanism
Payload	g	Part mass	Feedable mass
Speed	s	Required cycle time	Feeding rate
Clean room compatible?	n/a	Clean environment required	Functions in a clean room
Vacuum compatible?	n/a	Vacuum required	Functions in a vacuum

Table 4-8: Product and Process based questions for definition of Feed class capabilities for the Micro Capability Taxonomy

Feed Class			
Characteristic	**Options**	**Product Question**	**Process Question**
Part Shape	P, B, D, Cy, Cx	What approximate profile / shape is the part?	What profile / shape part can be retained?
Part Size	L, M, H	What is the largest part dimension?	What is the feedable dimension?
Orientation – about horizontal	∞, 4, 2, 1	How many orientations within the plane are permissible?	How many orientations within the plane are possible?
Orientation – about vertical	∞, 4, 2, 1	How many orientations within the plane are permissible?	How many orientations within the plane are possible?
Fragility	L, M, H	How fragile is the part?	How controllable is the gripping force?
Payload	L, M, H	What is the part mass?	What is the maximum payload?
Speed	L, M, H	What is the required product output rate?	What is the maximum product feed rate?
Clean room compatible?	Y, N	Is a clean room environment required?	Can the system function in a clean room?
Vacuum compatible?	Y, N	Is a vacuum required?	Can the system function in a vacuum?

Table 4-7 provides an overview of the characteristics and their associated indicators for the Feed class. Table 4-8 shows the questions, from both the product and process perspectives, which will enable the capability to be defined by the user.

4.2.3.5 Key Differences in Micro Scale

The Taxonomy outlined in the preceding sections is focussed on the issues associated with assembly in the micro scale. It is built upon work by [Tietje, 2009] towards a Design for Micro Assembly methodological approach. A key point noted is that the majority of issues remain common with the macro scale; the primary differences can be derived from the forces acting upon the parts, as described in Section 2.3.1.2. The differences are addressed by the implementation of appropriate equipment, such as that developed in Test Case 3 of this thesis, which demonstrated that use of clean rooms and vacuums are often central to micro assembly.

4.3 Capabilities Modelling: Identification, Definition and Comparison

4.3.1 Capability Identification

The first step in the implementation of the Capability Model is the identification of the capabilities to be analysed. This is not necessarily a straightforward process as the concept of ‘capability’ is not intuitive. It is important to note that the process of defining Capabilities will differ for equipment-based capabilities and product-based capabilities.

The implementation of the six Capability Classes is an important facet of the process. The classes are generally representative of equipment types; for example, a bowl feeder feeds parts and so falls within the *Feed* class. This makes the definition process somewhat simpler, but it is still essential to have a structured process for the definition of the capabilities. *The identification is restricted to the number of capabilities and their class*; additional details are added during the definition.

4.3.1.1 Equipment Derived Capabilities

The derivation of capabilities from equipment modules is firstly a function of the six Capability Classes (reference Section 4.2.1), whilst the implemented Capability Taxonomy enables the full definition. Each Equipment Module is represented by an entry in the Equipment Library (reference Section 6.2.3), each will fall into one of two availability classifications: *Available* or *Procurable*. *Available Modules* are those that can be integrated within the system without affecting the lead-time of the configuration (i.e. they will be available prior to the reconfiguration being started). *Zero-Cost Modules* are a subset of *Available Modules* and are defined as modules that additionally do not incur a financial cost in their integration within the new system configuration(s). Thus, such modules must be i) previously procured with no outstanding financial payments (excluding normal maintenance and running costs) and ii) physically present and available to the system at its location (or at least will be before integration commences).

Effectively, *Available Modules* and *Zero-Cost Modules* refer to the same set, however; *Zero-Cost* has a definition that is more specific than *Available*. CAMARA proposes that the *Available Module* list comprise of only *Zero-Cost Modules*, but allows for the manual inclusion of modules by the user. This enables the user to use discretion in the determination of the modules that are available as there may be conditions whereby it is more appropriate to include a module in the *Available* list than the *Procurable* list. For the purposes of this thesis, the list will be referred to as the *Available Module* list. Furthermore, the majority of the model is described around the assumption that there is a single Available Module, and hence single Available Capability, set. The case of multiple sets is dealt with in Section 4.4.1.1 and Section 4.4.1.2.

It is anticipated that the majority of *Available Modules* will be those modules present in the system, but some will also be from other systems or from storage. It is proposed that the latter case will become more common over time: as manufacturers implement more RASs, procure more modules and operate shorter production runs, there are likely to be unused modules[2]. Typically, any excess capacity or capability in an assembly system is not tolerated as it incurs cost without delivering benefit. However, the combination of the RAS paradigm aligned with the CAMARA approach offers the potential for companies to invest in a ‘pool’ of equipment modules that offer the projected range of requirements for the assembly of proposed product ranges.

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[2] Such a situation assumes that the concept of equipment module leasing or rental, as proposed by [EUPASS, 2008], has not been widely implemented within industry.

By minimising this equipment pool, and determining its size and cost prior to implementation, the system configuration lifecycle can be evaluated. This concept is expanded and detailed in Section 5.3.5.

The *Available Capabilities* set is derived from the *Available Module* set through the application of the Capability Taxonomy. As is the case with all of CAMARA, the user is assumed to be an expert: i.e. familiar with the technologies, equipment and terminologies. The user drives the software presented in Chapter 6, which guides the identification process. The identification of the equipment capabilities is based around the definition of the six Capability Classes – their definition guides the criteria that enable the capabilities to be identified. The derivation of these classes is described in Section 4.2.1

The most important point is that all of *the only capabilities of the equipment modules considered within the context of this thesis approach are with respect to functionality that can be directly imparted on the product*. This is an important point: a module may have, for example, linear actuators that move a tray of parts into position – this is encompassed within the 'Feed' capability. The specific characteristics of each class are detailed below.

Move: *The module induces relative motion between a product or component (part) and another point in the system.*

Relative motion between the product and the module is the important consideration: in many cases, the product or component will be moved but in other cases the part will be fixed and an end-effector will be moved. For example, if a line of adhesive is required on a part, either the part can be moved across a stationary dispenser, or the dispenser can be moved across the stationary part. The net effect, and description, is the same.

Join: *The module restricts the relative motion between two parts in at least one degree of freedom.*

The joining of parts is the core of assembly. It is the ultimate aim, but is relatively simply described. Any process that restricts relative motion between two (or more) parts is considered to be joining. Because of this definition, any motion system has the potential to induce a Join in the form of an insertion.

Retain: *The module restricts the relative motion between a part and another point in the system in at least one degree of freedom.*

The retention of parts in fixed positions prior to assembly is essential for automated assembly. This retention is rarely of a part onto a fixed part of the system, but rather on a motion module so that the part can be moved.

Measure: *The module observes, without altering, a phenomenon, characteristic or property related to a part of assembly and records the result quantitatively or qualitatively.*

Measurement is an intrinsic part of modern assembly as a means of ensuring quality. The measurement is conducted by a module that does not alter the part or assembly.

Feed: *The module presents a single part at a defined location, in a defined orientation.*

Feeding is the process whereby individual parts are made available to other modules within the system from the bulk delivery. The modules may have some internal motion but this is not considered as a capability.

Work: *The module induces a change in the properties of a part by the additional or removal of material or the alteration of properties through the application of temperature, pressure or force.*

Work can encompass a broad range of processes, from machining to coating. They are not strictly assembly processes and rarely included in assembly lines[3]. Thus, whilst they have been accounted for in the Taxonomy and in the model, the specific conditions of their implementation is not considered as part of this thesis. These definition terms can be used in the generation of a decision flow chart that identifies the class of capabilities associated to a module, which is described in further detail in Section 4.3.2.1.

4.3.1.2 Product Derived Capabilities

In parallel to identifying the equipment-derived capabilities, the product-derived capabilities must also be identified. This is a more complex process as

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[3] Generally, dedicated machines deliver such functions. The removal or addition of material is not usually compatible with assembly as residual material ‘floats’ in the air, interfering with other parts and processes. Thus these processes are often not included within modular systems.

the identification is of the capabilities a system is required to have in order to deliver a particular product. Thus a more structured tool is required to guide and aid the user in the identification process. As with the equipment-derived capability identification, the product-derived process focuses on identifying the class of the capability as this is the fixed and common feature of the *Capability Taxonomy*: the definition is completed later and is dependent on the taxonomy used. The product-derived capabilities are identified one product at a time to provide the clear capability sets that are analysed later in the approach.

One important aspect, which must be defined prior to the implementation of the approach, is the assembly sequence. The assembly sequence is the order in which parts are assembled together to deliver the compete product. Further to this, each part and the relationships between them (the liaisons) should be defined to the level of detail available. This is part of the *Requirements Elicitation and Definition*, described in Chapter 6. With the parts and assembly sequence defined, the process of identifying the capabilities can commence. This is done through use of a *Process Flow Template* and the *Capability Taxonomy* within the *Capability Identification* process.

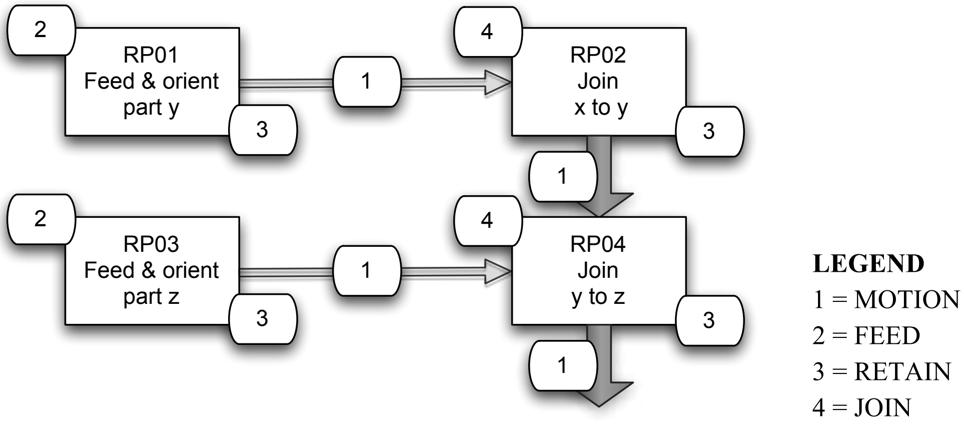


Figure 4-5: Example of the Process Flow Template

The *Process Flow Template*, of which an example is shown in Figure 4-5, is based upon the principle that assembly requires two parts to be brought and maintained together. It is derived from the informal flow diagrams used in industry to represent assembly and processing sequences [Smale, 2006]. Therefore, the core assembly processes are “Moving Part x” and “Joining Parts x and y”. The template is constructed through a structured process, as detailed below. The Process Flow Template itself must be understood in order for it to be successfully utilised. The key features of the template are:

- Each part is addressed individually, in the order of the assembly sequence. This ensures that, from the outset, the requirements and capabilities are correctly ordered and the user can focus on an individual element rather than being overwhelmed by the needs of the entire product[4].
- There are two columns of boxes. They have separate and specific purposes and are notated as Left Hand Boxes (LHB) and Right Hand Boxes (RHB).
- Directional arrows to signify the chronological flow of processes and events connect the boxes. This is the “Flow” of the template.
- Each box is populated with the appropriate statement (which may be “N/A”) regarding the assembly of the product.
- The boxes are connected by directional arrows to signify the process flow.
- The application of defined rules to the completed template converts it into the *Capability Flow Diagram*, which identifies and locates all of the capabilities require to deliver the product[5].
- The capabilities are identified on the diagram by a numerical representation:
    1. = Motion Capability
    2. = Feed Capability
    3. = Retain Capability
    4. = Join Capability
    5. = Work Capability
    6. = Measure Capability

---

[4] Whilst the example products during this thesis consist of relatively few parts, in reality the High-value, high-complexity, low-volume products that this thesis focuses on often comprise of a large number of parts.

[5] Some of these capabilities will later (during the definition process) be set to ‘zero’ and have no value because they do not exist.

The completion of the template is achieved, as stated previously, by either manual or automated methods. The manual method makes the process and purpose clearer and gives the user a better understanding of what needs to be done and why. As with all or part of the CAMARA approach, it is proposed that any user become familiar and comfortable with the manual approach. The manual creation of the Process Flow Template for a product is outlined below:

1. Select the first part in the assembly sequence.
2. Enter the part reference into the first free RHB.
3. Into the same box, add the liaison that must be met. (In the case of the first part this will be with the fixture rather than another part).
4. In the LHB adjacent to the last-used RHB, enter the same part reference.
5. Connect these two boxes with an arrow directed towards the RHB.
6. Select the next part in the assembly sequence and repeat from (2) until all parts are detailed.
7. For each measurement and work operation to be completed as part of the assembly, populate a separate RHB.
8. Locate each of these RHBs in the correct location in the sequence.

This will produce the first stage of the Process Flow Template. In this form, it is a series of technical statements that describe the required processing. To this template, a number of rules can be applied that will translate the information into the Capability Flow Diagram. The first of these rules are based upon the construction of the template itself:

I. **All Left hand Boxes (LHB) are Feeding Processes.**
II. **All Right Hand Boxes (RHB) that are directly connected to an LHB are Joining Processes.**
III. **All other RHBs can be any of Motion, Join, Measure or Work.**
IV. **Horizontal arrows, connecting LHBs to RHBs, are Motion Processes.**
V. **Vertical arrows, connecting RHBs to RHBs, are Conveying Processes, which are not included at this stage.**

In addition, it is possible to extract certain rules from the capabilities themselves and their interdependencies:

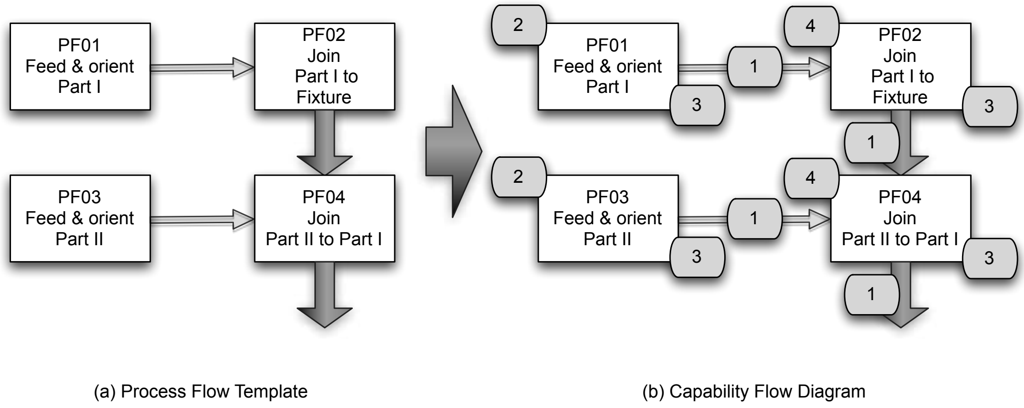
VI. **Any Motion Process must be preceded by a Retaining Process (Gripping).**

VII. **Any Conveying Process must be preceded by a Retaining Process (Fixture).**

VIII. **Any part that is Gripped and Moved, must be released – therefore it must be Joined.**

In addition to the structured method described above, the user is also able to add additional boxes into the sequence to represent any processes not covered by elsewhere. Such processes are not foreseen at this stage of the research, and the user must take the responsibility for ensuring the accuracy of the data, but the facility exists should it be needed.

One important factor is that the Capability Flow Diagram does not represent the workstation or cell layout and does not include the transfer of parts between workstations as that is a line balancing issue and could be prescriptive at this stage of evaluation. In addition, any capability within the diagram can be set to zero or null. This allows for the use of very strict rules in the construction of the diagram whilst the zero-value capabilities will be identified during the definition process. An example of the application of these rules to the *Process Flow Template* to produce a *Capability Flow Diagram* is shown in Figure 4-6.



(a) Process Flow Template

(b) Capability Flow Diagram

Figure 4-6: Illustration of the Capability identification process for products, from (a) the Process Flow Template to (b) the Capability Flow Diagram

The *Capability Flow Diagram* clearly identifies the required capabilities for one product: one diagram is needed for each product. Each diagram is used to generate the list of capabilities, the *Required Capability Sets*, for each product. These are logged and used in the next stage of the model.

4.3.2 Capability Definition

With the *Available* and *Required Capability Sets* identified, the next phase of the model is Capability Definition. During this phase, the capabilities are individually defined with respect to the relevant taxonomy. This stage of the process requires that each capability be addressed separately and that the taxonomy be utilised in a format that can be queried.

In order for the taxonomy to be re-defined into a form that can be queried, each statement of function that comprises a single tier of the hierarchy must be changed to a question to which each branch is an answer. An example of this is demonstrated below.

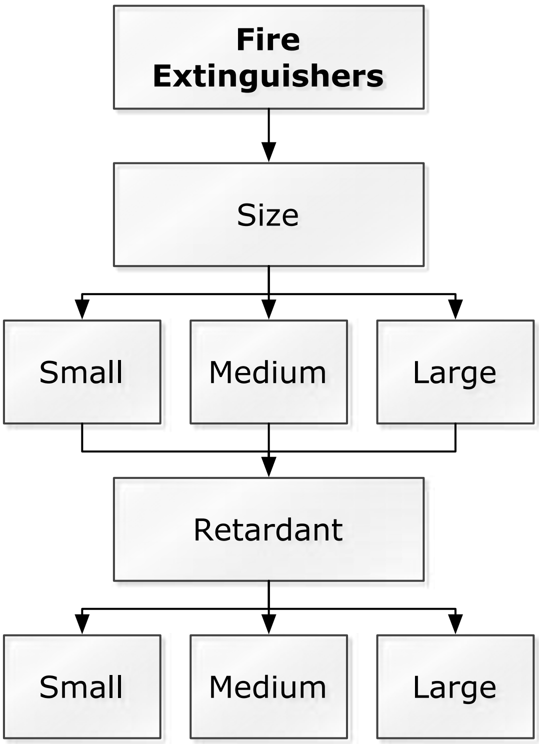


Figure 4-7: Illustration of the small example taxomony

A small taxonomy is used to describe the fire extinguishers employed within a building, shown in . The first category is *'size'* with three options: *'small'*, *'medium'* and *'large'*. The second category is *'retardant material'* also with three options: *'water', 'foam'* and *'CO_2'*. Therefore the possible questions derived for the two levels are *'what size is the extinguisher?'* and *'what retardant material is used by the extinguisher?'* respectively. As discussed in Section 4.2, the taxonomy is designed to use linguistic classifiers, even where specific numbers may be known, to ensure that both the use and upgrading of the taxonomy is as simple as possible. This has an impact on the format of the answers given. Whilst the answers to the second question will be selected from the linguistic classifiers, *'water', 'foam'* or *'CO_2'*, the first question could be answered by one of two methods: either the selection from the list of linguistic classifiers (*'small'*, *'medium'* or *'large'*) or the entry of a specific and finite value (e.g. 30 litres). Ultimately, the linguistic classifiers will have boundaries in order to be defined, so a numerical definition is not problematic. However, the purpose of the use of linguistics is that where details are not known or defined, sensible approximations can be made. Therefore the most suitable approach is to offer both answering options and for the model to translate where necessary.

The chosen Capability Taxonomy is applied in order to define each individual capability and is tabulated such that by answering a series of questions the capability can be defined. The output is a numerical value, which is then logged within the relevant set. The process is repeated for each process associated with a product to complete that product's required capability set. The entire process is repeated for each of the products.

As a result of the use of the linguistic classifiers, the taxonomy will have a finite number of capabilities available. So, whilst each capability is numerically defined, there is also a reference number. In the case of frequent use of very similar parts, or simply the user's familiarity with the model, the option will be available to manually enter the definitions or the reference number directly. As with other such functions, it is essential that the model identify such capabilities as 'manually defined' so that the system's traceability is maintained. The subsequent sub-sections describe and illustrate the definition process and method associated with the specific Capability Taxonomies described in this thesis.

4.3.2.1 Capability Class Definition

The first step in the definition process is the decision regarding the class of the capability. In the case of the Required Capabilities, this is found as part of the Capability Identification process, described in Section 4.3.1.2. However, as outlined in Section 4.3.1.1, it is more complex for the Available Capabilities. In order for the Capabilities to be defined, the classes must also be identified. Because the identification and definition of Available Capabilities will be performed through the observation of the equipment, the process must be based upon observational questions.

To a large extent, and given the assumption that the user is an expert in assembly and manufacturing, the class of capability/ies that a module has are immediately identifiable without guidance. However, for clarity and consistent application a series of pertinent questions should be used.

In order to ensure that multiple capabilities are not missed and that false capabilities are not identified (such as the motion a feeder induces in a part does not constitute a 'Move' class capability) the questions and their sequence are carefully considered and structured. There are a number of assumptions based on common equipment structures that are termed the 'Module Rules', which influence the identification and definition:

- A work module cannot provide another capability.
- A measure module cannot provide another capability.
- A feed module cannot provide another capability.
- A motion module is likely to offer a join capability when combined with a retaining module – therefore this requires consideration after the definition of all of the modules.

Note: in all instances, the term 'part' refers to any component or sub-assembly of the product being assembled. The questions are:

1. Does the module induce a change in the properties of a part by the addition or removal of material or the alteration of properties through the application of temperature, pressure or force? [YES = WORK]

2. Does the module observe, without altering, a phenomenon, characteristic or property related to a part and record the result? [YES = MEASURE]
3. Does the module isolate a singular part from an input of bulk parts and present it in a specified orientation? [YES = FEED]
4. Does the module induce controllable relative motion between a product or component (part) and another point in the system? [YES = MOTION]
5. Does the module restrict the relative motion between a part and another point in the system in at least one degree of freedom? [YES = RETAIN]
6. Does the module restrict the relative motion between two parts in at least one degree of freedom? [YES = JOIN]
7. Does the module offer another capability listed?
8. Consider the module architecture; separate functionality to create additional module/s.

The sequence of the questions does have an impact – equipment that are primarily used for working, measuring or feeding may well also, by these questions, offer motion and/or retaining capabilities. However, with respect to the purpose of the capability comparison and allocation (described in later sections), such items of equipment cannot be viewed in such a way because it is required that one module have one capability. Furthermore, the definition of a Capability from Section 4.3.1.1 is that *the equipment modules' capabilities are only with respect to functionality that can be directly imparted on the product* so any motion that cannot be exerted relative to the product are not included.

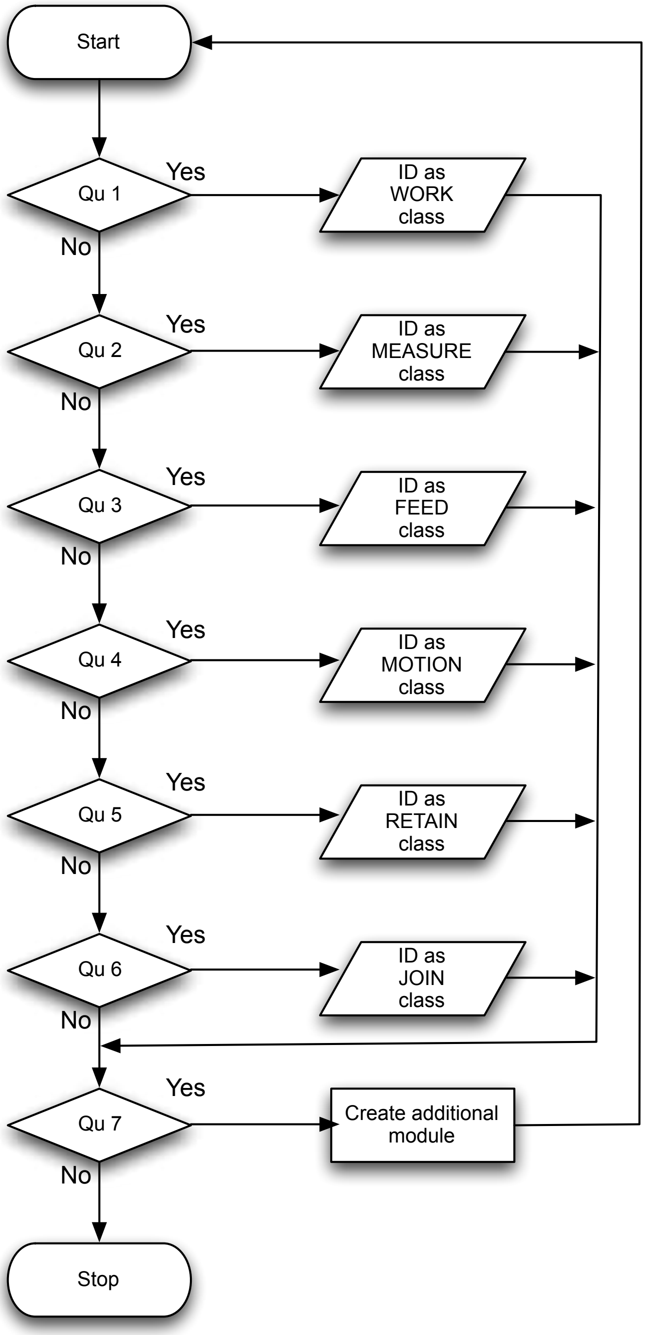


Figure 4-8: Flow diagram for the determination of capability classes for an equipment module.

These definition terms can be used in the generation of a decision flow chart that identifies the class of capabilities associated to a module. This chart is termed the *Equipment Capability Identification Chart* and is shown in Figure 4-8. This chart forms the basis of both a manual and a software-based tool for capability identification. The manual tool requires that, for each equipment module, the *Equipment Capability Identification Chart* is used to find the class of the capabilities that each module has. These can be noted and the information logged. The data will then be extended by the addition of the full capability definition, as described in Section 4.3.2. Thus, the *Available Capability Set* is generated and utilised in the definition stage of the model.

4.3.2.2 Capability Detail Definition

The nature of the definition process is common to the approach, regardless of the exact taxonomy used. The user is presented with a series of questions (which are different dependant on whether the user is a Customer/System Integrator or an OEM) the answers to which provide a definition for the capability in question. For the purposes of conciseness, the complete definition information is not presented here, but can be referenced in Appendix A.

4.3.3 Capability Comparison

The final step in the Capability Model is to perform a comparison of the capability sets. For this purpose a Comparison Matrix is used, an example of which is shown in Figure 4-9. The Comparison Matrix was developed as a solution to the desire for a logical representation of the comparison process. Matrices are often used within both manual methods and in software for the storing and sequencing of data – as the comparison process requires both of these elements, a matrix approach was selected.

The Comparison Matrix has been devised in order to enable two or more capability sets to be compared. In the case of an existing equipment pool, the capability set for the pool populates the top row of the matrix and is used as the basis for the comparison. In the case that there is no pre-existing system then the first product's capability set is used. The remaining capability sets are listed down the first column and the comparison performed.

However; comparison is not always straightforward. Two capabilities do not have to be equal in order to be compatible. For example, two motion capabilities that are identical except for that one is high precision and one low precision. A straight comparison would show these to not be equal, but the same (higher specification) equipment module could deliver them. It should also be noted that if they are not required at the same location then two different equipment modules will be required and thus there would be no sense in over-specifying one of them. *Therefore the Comparison Matrix does not only identify equal capabilities but also compatible capabilities*.

Each location (intersection in the matrix) is populated with a number; with 1 representing an exactly matching capability (*High Match*), 0.1 representing a compatible capability (*Low Match*) and 0 no match. Each row and column is totalled at the end of the analysis and these figures logged for later use in the Reconfiguration Methodology. The numbers are also used to identify the Boundary Configurations or to provide any other capability-based configuring.

		EXISTING SYSTEM										
		A1.1	A1.2	A1.3	A1.4	A2.1	A3.1	A3.2	A3.3	A5.1	A5.2	**TOTAL**
NEW PRODUCT	B1.1	1	:1	0	:1							1:2
	B1.2	:1	1	:1	:1							1:3
	B1.3	0	0	:1	:1							0:2
	B2.1					0						0
	B2.2					0						0
	B3.1						1	1	0			2
	B3.2						:1	:1	0			0:2
	B3.3						0	0	0			0
	B3.4						:1	0	0			0:1
	B5.1									1	0	1
	B5.2									0	0	0
	B5.3									0	:1	0:1
	TOTAL	1:1	1:1	0:2	0:3	0	1:2	1:1	0	1	0:1	

Figure 4-9: An example Capability Comparison Matrix

4.3.3.1 Refining the Capability Lists

The next stage of the methodology is to analyze the comparison results to determine the optimum configuration for each product. The exact nature of this analysis will be dependant on the *Reconfiguration Scenario* selected, as this will determine the priority outcome for the configuration. However, the analysis will follow a broad pattern regardless of the *Reconfiguration Scenario*. The generation of the *Capability Lists* is based upon:

- All of the *Existing Capabilities* with a total compatibility score of zero (i.e. cannot deliver any of the *Required Capabilities* for this configuration) are logged in the ***'Surplus Capabilities'*** list.

- All of the *Required Capabilities* with a total compatibility score of zero (i.e. cannot be delivered by any of the *Existing Capabilities*) are logged in the ***'Procure Capabilities'*** list.
- The remaining *Existing Capabilities* are allocated *Required Capabilities* based upon criteria dictated by the *Reconfiguration Scenarios*; these relationships are logged in the ***'Consideration Capabilities'*** list.
- The *Consideration Capabilities* list is the area focussed on for analysis by the *Reconfiguration Methodology* as it represents those capabilities to which a definitive answer regarding their status in the configuration cannot be given: the *Surplus* and *Procure* lists are definitive.
- If relevant, after further analysis, the *Surplus Capabilities* and *Procure Capabilities* lists will be updated.

The aim of the further analysis is to move all of the capabilities in the 'Consideration' list into either the 'Procure' list (for Required Capabilities), the 'Surplus' list (for Available Capabilities) or into a new list: Matching Capabilities.

Matching Capabilities are those that are confirmed as being implemented as a match within the relevant configuration. This means that the entries in the list will consist of at least two capabilities each: one Available and one Required.

4.3.3.2 Defining the Boundary Configurations

The concept of 'Boundary Configurations' is that for any given reconfiguration requirement, there is a range of possible solutions. This could encompass a very large number of possibilities, but it can be assumed that in an industrial application only the realistic and feasible solutions need to be considered. This range of options is bounded by a maximum and a minimum.

The *Maximum Reconfiguration* is the case in which the most reconfiguration cost and effort is encountered. In this case, only the exact matching Existing Capabilities are retained; any other 'minor matches' or missing capabilities are required to be procured and are done so with exact matching modules. Furthermore, the configuration is made such that each module only has one Required Capability to deliver. This may result in additional procurement costs.

The *Minimum Reconfiguration* is the case in which the minimal effort and cost is incurred in the reconfiguration of the system for the delivery of the product. In such a case, equipment re-use is prioritised so that, wherever possible, the Available Capabilities are used. Where the existing system cannot deliver the requirements, the procurement is focussed on minimising the number of new modules. It should be noted that in certain cases it is foreseeable that the effort to reduce the number of modules results in an increase in cost (where cost of 1 complex module exceeds the cost of 2 or more simple modules) but the *Minimum Reconfiguration* is about the number of modules and the reconfiguration effort, rather than pure cost.

These configurations offer the boundary to the area in which the solution configuration will be found. It is hypothesised and proposed that evaluation and projection based upon these boundaries may enable the relevant stakeholders to make better-informed decisions. Such information could be presented in the form of graphs that assume a linear relationship, however, this assumption is rather unsatisfactory. Instead it is proposed that a third point on the graph be plotted to identify the approximate shape of the graph.

This mid-point is the *Mean Reconfiguration* and is derived by an approximation: the difference in procured capabilities between the Maximum and Minimum Reconfigurations is halved and the same principle applied to the retained capabilities. This will give a very rough configuration, which may not be completely coherent and should be manually altered to make it more realistic. This then offers the additional plot required to define the approximate shape of any curve in the performance projections charts.

4.3.3.3 Calculation of Boundary Configurations

In order to find the boundary configurations, it is necessary to provide a standardised calculation method. Without a standardised and common approach, the results of the work would not necessarily be comparable across projects or even if the same project is re-calculated based on limited changes.

The calculations are based upon the Comparison Matrix having been used and the Three Capability Lists (Surplus, Procure and Consideration) generated. From this starting point, the three boundary configurations can be found as detailed in Table 4-9 to Table 4-11.

Selection of the appropriate solution, or range of solutions, from the Configuration Scale is left to the discretion of the user. The core principle behind CAMARA is that it assists and supports decision-making rather than trying to fully automate the process.

Table 4-9: Summary of the Capability Lists for the Maximum Configuration

Maximum Configuration	
Aim	Reconfigure the maximum number of modules
Capabilities to Retain	High Matches only
Capabilities to Remove	All other Existing Capabilities
Capabilities to Procure	All other Required Capabilities

Table 4-10: Summary of the Capability Lists for the Minimum Configuration

Minimum Configuration	
Aim	Reconfigure the minimum number of modules
Capabilities to Retain	High Matches + Low Matches
Capabilities to Remove	Existing Capabilities with matches = 0
Capabilities to Procure	Required Capabilities with matches = 0

Table 4-11: Summary of the Capability Lists for the Mean Configuration

Mean Configuration	
Aim	Reconfigure the intermediate number of modules between maximum and minimum
Capabilities to Retain	High Matches + 1/2 Low Matches
Capabilities to Remove	Existing Capabilities with matches = 0 + 1/2 Low Matches
Capabilities to Procure	Remaining Required Capabilities

It can therefore be seen that by reducing the size of the Low Matches capability set, the possible range of configurations is minimised. This is the result of the Low Matches being the primary variable; the Maximum Configuration requires all of these to be replaced, whereas the Minimum Configuration requires that none of these be replaced. The implementation of the *Elimination Methodology* ensures that the Low Matches capability set is minimised.

4.3.3.4 *The Elimination Methodology*

The *Elimination Methodology*, which is demonstrated in detail in Appendix B, is based on the assumption that the goal is to reconfigure as cost-effectively as possible. In other words, every Existing Capability that can be re-used is re-used, but also the Required Capabilities are distributed across as many Existing Capabilities as possible; minimising the Procure Capability set.

The method is based upon other assumptions, including that Existing Capabilities have no monetary value and so removing them does not hold financial benefits. Consideration of the trade-in value of modules is not considered by this research at this stage. Only totally redundant capabilities are removed. Linked to the above, the Required Capabilities are distributed across as many Existing Capabilities as possible - the use of the Existing Capabilities which are present is maximised.

4.4 Summary

One of the main outcomes from the Capability Model is the ability for a System Integrator to confirm whether or not proposed products can be delivered by existing systems. This confirmation could be all the information the Customer is looking for at this stage.

However, there may be more detailed questions that need answering. Particularly with respect to the details of the configurations needed to provide a solution and refining solutions to optimise them for particular situations or scenarios. For this reason, a Reconfiguration Methodology is proposed in Chapter 5.

4.4.1 Proposals for Expansion of the Model

The primary role of this model is to identify if and how a single RAS can be reconfigured to deliver various products. However, the same principles can be applied to determine different results.

4.4.1.1 *Single Product, Multi System*

This variant enables the allocation of a single product to one of multiple lines. This variant utilises a different Comparison Matrix in which a single product is compared to multiple systems in order to find which of the existing lines is best suited to the delivery of the product in question.

In this application, the identification and definition processes are completed in the same manner – the significant being that there are more Available Capabilities to define than Required Capabilities.

One Comparison Matrix is created for each existing system and each is populated with the relevant Available Capabilities and with the Required Capabilities, which will be the same in all cases.

The comparison itself is also performed in the same manner and is repeated for each of the created matrices. The results of the comparison are used to identify which of the available systems can deliver the required product. Should none of them be able to, then the system closest to being able to can be identified.

4.4.1.2 Multi Product, Multi System

This variant enables the multiple-line to multiple-product allocation. This is a combination of the main application of the approach and of the first expansion, described in Section 4.4.1.1.

This approach requires a great deal of computational effort as, in principle, each product needs to be compared to each of the available systems. How this expansion is applied would depend upon the goals and intentions of the users. If the customer is looking to produce one product on each line, then the method of evaluation will be different from that applied if the aim is to find the line most suited to producing all of the products: such considerations are outside of the scope of this thesis.

4.4.2 Summary of Example Application

In order to demonstrate the principles and function of the Taxonomy and Model, a simple example application is used. This example is entirely fictitious and is used only to evaluate the process the user goes through – the results of the comparison are not the priority at this stage as they must be interpreted by the, as yet undefined, Reconfiguration Methodology. The example consists of an existing system and two new products, detailed in Table 4-12.

This variant enables a manufacturer to project what capabilities, and thus what equipment modules, are likely to be the most effective to acquire in order to deliver a continually evolving set of products.

Table 4-12: Summary of example test case

Simple Fictional System	Sensor Product	Valve Product
1 x 6-axis robot (A1.1)	1 x base component	1 x base
2 x 4-axis robot (A1.2 – 1.3)	1 x processor chip	1 x switch
3 x mechanical gripper (A3.1 – 3.3)	1 x top case	1 x top case
1 x adhesive dispenser (A2.1)	1 x sensor element	1 x manifold
1 x bowl feeder (A5.1)		1 x manifold seal
1 x tray feeder (A5.2)		1 x switch button
3 x emergent joining capabilities (A2.2 – 2.4)		

Using the Capability Identification process, including the Process Flow Template for the products and the decision diagram for existing equipment alongside the Capability Taxonomy, a list of capabilities is generated for each element. The capabilities are given an alphanumeric title; the letter represents the associated element, in this case A = SFS, B = FSP and C = FVP. The first number represents the capability type, therefore 1 = Motion, 2 = Join, 3 = Retain, 4 = Measure, 5 = Feed and 6 = Work. The number after the decimal point is the number for the particular capability. This results in the following capabilities:

- Available Capabilities (from Existing System): A1.1, A1.2, A1.3, A2.1, A2.2, A2.3, A2.4, A3.1, A3.2, A3.3, A5.1, A5.2
- Required Capabilities 1 (from New Sensor Product): B1.1, B1.2, B1.3, B1.4, B1.5, B2.1, B2.2, B2.3, B2.4, B3.1, B3.2, B3.3, B3.4, B3.5, B5.1, B5.2, B5.3, B5.4
- Required Capabilities 2 (from New Sensor Product): C1.1, C1.2, C1.3, C1.4, C1.5, C1.6 C2.1, C2.2, C2.3, C2.4, C2.5 C3.1, C3.2, C3.3, C3.4, C3.5, C3.6 C5.1, C5.2, C5.3, C5.4, C5.5

Table 4-13: Comparison Matrix A - comparing Existing System to Sensor Product

		EXISTING SYSTEM												
		A1.1	A1.2	A1.3	A2.1	A2.2	A2.3	A2.4	A3.1	A3.2	A3.3	A5.1	A5.2	**TOTAL**
NEW PRODUCT	B1.1	1	0	0										1
	B1.2	:1	1	0										1:1
	B1.3	:1	1	0										1:1
	B1.4	:1	:1	0										:2
	B1.5	:1	0	0										:1
	B2.1				0	1	0	0						1
	B2.2				0	0	:1	0						:1
	B2.3				0	0	0	0						0
	B2.4				0	0	0	0						0
	B3.1								1	0	0			1
	B3.2								1	0	0			1
	B3.3								:1	0	0			:1
	B3.4								:1	0	0			:1
	B3.5								0	0	0			0
	B5.1											1	0	1
	B5.2											1	0	1
	B5.3											0	1	1
	B5.4											0	:1	:1
	TOTAL	1:4	2:1	0	0	1	:1	0	2:2	0	0	2	1:1	

Table 4-14: Comparison Matrix B - comparing Existing System to Valve Product

		EXISTING SYSTEM												
		A1.1	A1.2	A1.3	A2.1	A2.2	A2.3	A2.4	A3.1	A3.2	A3.3	A5.1	A5.2	**TOTAL**
NEW PRODUCT	C1.1	:1	1	0										1:1
	C1.2	:1	:1	0										:2
	C1.3	:1	:1	0										:2
	C1.4	:1	0	0										:1
	C1.5	:1	0	0										:1
	C1.6	:1	0	0										:1
	C2.1				0	1	0	:1						1:1
	C2.2				0	1	0	:1						1:1
	C2.3				0	0	0	0						0
	C2.4				0	1	:1	0						1:1
	C2.5				0	0	0	0						0
	C3.1								:1	0	0			:1
	C3.2								:1	0	0			:1
	C3.3								0	0	0			0
	C3.4								0	0	0			0
	C3.5								0	0	0			0
	C3.6								:1	0	0			:1
	C5.1											0	0	0
	C5.2											:1	0	:1
	C5.3											:1	1	1:1
	C5.4											1	0	1
	C5.5											0	0	0
	TOTAL	:6	1:2	0	0	3	:1	:2	:3	0	0	1:2	1	

Using the Comparison Matrix, comparisons can be made between the Existing System and the Sensor (Matrix A: Table 4-13) and between the Existing System and the Valve (Matrix B: Table 4-14). From this, the following conclusions can be drawn:

- Existing Capabilities A1.3, A2.1, A3.2 and A3.3 have totals = 0 and are therefore redundant.
- Required Capabilities B2.3, B2.4, B3.5, C2.5, C3.3, C3.4, C3.5, C5.1, C5.5 have totals = 0 and must therefore be procured.
- The other capabilities have some degree of match.

From these initial Capability Lists, it is then possible to identify the boundary configurations. The Maximum Configuration utilises only exact matches between Required and Existing Capabilities, whilst the Minimum Configuration utilises all matches. Thus the two configurations can be described, as shown in Table 4-15.

Table 4-15: Description of the capabilities to retain and to procure for the Maximum and Minimum Configurations associated with the Sensor and Valve products.

	Maximum Reconfiguration		Minimum Reconfiguration	
Sensor Product	C_{RT}	A1.1, 1.2, 2.2, 3.1, 5.1, 5.2	C_{RT}	A1.1, 1.2, 2.2, 2.3, 3.1, 5.1, 5.2
	C_{PR}	B1.3, 1.4, 1.5, 2.2, 2.3, 2.4, 3.2, 3.3, 3.4, 3.5, 5.2, 5.4	C_{PR}	B2.3, 2.4, 3.5
Valve Product	C_{RT}	A1.2, 2.2, 5.1, 5.2	C_{RT}	A1.1, 1.2, 2.2, 3.1, 5.1, 5.2
	C_{PR}	C1.2, 1.3, 1.4, 1.5, 1.6, 2.2, 2.3, 2.4, 2.5, 3.1, 3.2, 3.3, 3.4, 3.5, 3.6, 5.1, 5.2, 5.5	C_{PR}	C2.3, 2.5, 3.3, 3.4, 3.5, 5.1, 5.5

Finally, by considering the equipment associated with each capability, the following equipment-oriented statements can be made:

- Of the existing equipment, 4 modules are redundant and no longer required: 1 SCARA, 2 grippers and the glue dispenser.
- For the new systems to function, at least 6 modules are required: 0 Motion, 2 Join, 4 Retain, 0 Measure, 2 Feed and 0 Work.
- The remaining capabilities have various degrees of compatibility, which must be further evaluated.

5 Reconfiguration Methodology for the Generation of Optimised Assembly System Configurations

A reconfiguration of a system can comprise of any substantial alteration of the physical and/or control attributes of the existing configuration. Within this thesis, *a reconfiguration is a change of the physical modules within a system through any combination of equipment removal, addition, exchange or relocation. It is induced by a change in system requirements or operational conditions and is likely to require that the control system be altered.*

This definition provides the basis for the purpose of the Reconfiguration Methodology: it must enable the system in question to be successfully and efficiently reconfigured. Further to this, the methodology should also offer the ability to provide a 'quick-look' at configuration options and implications, before providing the more detailed information required to realise the changes. This follows the same overall theme of the Capability Model (Chapter 4).

The Capability Model provides the parameters for the Reconfiguration Methodology to operate: the requirements and Reconfiguration Scenario have been defined and the Required and Available Capabilities have been translated into the Capability Lists that enable configurations to be considered at the capability level.

The Reconfiguration Methodology will output the results to a number of external systems, tools and ways-of-working. These are, although broadly common in type to all applications, potentially highly variable in specific nature and so must be considered generically for this thesis. This Chapter provides an overview of the methodology and its key elements, which are described in greater detail.

5.1 Description of the Proposed Methodology

5.1.1 Overview of the Reconfiguration Methodology

The Reconfiguration Methodology has the overall objective of taking the results of the Capability Comparison and delivering a coherent *System Configuration Lifecycle*. The *System Configuration Lifecycle* comprises of the individual system configurations, defined at the equipment module level, and the sequence and details of the reconfigurations. The delivery of the System

Configuration Lifecycle requires several stages, which are integrated to form the *Reconfiguration Methodology*. The key elements of the *Reconfiguration Methodology* are described in the subsequent sections.

5.1.2 Requirements and Priorities for Assembly System Reconfigurations

One of the most fundamental aspects of the Reconfiguration Methodology is clarity of the requirements for assembly system reconfiguration. This can differ from the requirements for a completely new assembly system, primarily due to the consideration of the existing equipment, but also because of the likely situations in which RAS are to be implemented.

5.1.3 Motivation for Reconfiguration

In order to establish the requirements and priorities associated with system reconfiguration, one of the first elements is to understand the reasons for performing the reconfiguration. A core element of this development is a Cause-Effect tree, in which the effect is always a system reconfiguration. Within the tree, the causes are better described as “drivers” as they drive the reconfiguration.

An important point to note is that all of the drivers eventually lead back to the desire of the customer to increase their profits. Therefore, the drivers for reconfiguration will be investigated from two angles: the first is to investigate the technical changes made and the reasons for them and the second is to look at the financial motivators. This approach is necessitated by several factors:

- The customer company’s management may not have requirements beyond the increasing profit and so may be unable to extract any firm requirements for the project or, perhaps even worse, may have guessed at the requirements without investigating or understanding the implications.
- The technical management or operator may be driving the reconfiguration from a purely technical standpoint (i.e. replacement of operational equipment) and may not appreciate the financial implications of the decisions.

It is not desirable to make an assumption that, when project requirements are unavailable, they will remain the same as for the existing system because that requires establishing those requirements. This can only be achieved through either the customer specifying them, or the specification of the existing product and extrapolating based on the current configuration.

5.1.3.1 Causality Tree for System Reconfiguration

Table 5-1: Summary of the Technical Drivers for reconfiguration

CATEGORY	CLASS	SUB-CLASS
PRODUCT	Product Change	Product replaced
	Component Change	Component added, removed, replaced
	Product Mix Change	Product added, removed
PROCESS	Process Mix Change	Process added, removed, replaced, moved
EQUIPMENT	Equipment Added	Duplicate capability, additional capability
	Equipment Removed	Temporary, permanent
	Equipment Replaced	Like-for-like, upgrade, downgrade
PROJECT	Requirement Change	Cost, cycle time, quality et al.
	Environmental Change	Space, conditions, parameters

The technical causes that drive the system reconfiguration are shown in Table 5-1, which only includes expected factors – failures are not included. It should also be noted that the tree has been created in order to identify single causes – multiple factors can, and probably will, apply. For this reason, there are no multiple terms, e.g. Products added as each addition is considered to be a separate factor. Furthermore; small changes to Products or Processes (such as dimensions, tolerances etc.) are regarded as New. This enables a clear line to be drawn and simplifies definitions. The Technical Drivers are outlined in Table 5-1

Because this work only considers planned reconfigurations, those drivers that are unplanned (such as equipment failure) are not considered at this stage. Furthermore, in this stage of analysis, only changes to the Required Capabilities are considered (However, the methodology and model is applicable for changes to the Existing Capabilities – it will still lead to the population of a Comparison Matrix with a disparity between the two sets of Capabilities).

5.1.4 Primary Reconfiguration Requirements

The primary requirements for reconfiguration can be divided into three key categories: *Cost (κ)*, *Performance (P)* and *Time (T)*. This has been derived from the work conducted in consultation with potential system customers, as described in … In these instances, those questioned focussed on issues such as system cost, operational cost, cost per part (Cost requirements), cycle time, output rate (Performance requirements) and integration time, installation lead time (Time requirements).

Each of these requirements can be represented by a multitude of different measurable and quantifiable factors, including those identified, but grouping them enables their early consideration in situations where specifics are not available, which is in-line with one of the key aims of this thesis, provide a ‘quick-view’ of the possibilities and implications of decisions.

These requirements are defined within four key areas:

1. Product. All available details regarding the product, component parts and their liaisons.
2. Equipment. Any specific points regarding equipment, such as preferred/vetoed suppliers or equipment types, maintenance facilities and operator experience
3. Environment. External factors, such as noise, vibration, cleanliness etc.
4. Priorities. The factors against which any solution must be made, such as overall cost, cost per unit, reconfiguration time, minimisation of equipment pool.

It is not suggested that this is an exhaustive list of all possible factors or priorities. However, this does form the basis for the initial investigation. The detail of these Requirements, along with the consideration of Priorities, and the simultaneous evaluation of both is presented in Chapter 6.

The *Cost Requirement* is the budgetary limit the customer has in the procurement of a new system or configuration. Generally, cost must be considered as the combination of two elements: the initial and the running costs. The initial costs comprise of the direct equipment costs in procuring the modules and the cost of integration (design, installation, programming etc.). The running costs are all of the costs associated with the production of the products, excluding the material and component part costs, typically including the power consumption (and any other similar overheads), equipment maintenance and any personnel costs. In the majority of cases, by far the largest portion of running costs comprises the cost of employees.

The *Performance Requirement* is the generic description for one key performance indicator (KPI) chosen by the customer. There are a number of standard KPIs in assembly automation, the most commonly used and defined being: *Cycle Time* , *Product Failure Rate* and *Production Output*.

The *Time Requirement* covers the issues associated with the time during which the system is not operational. It is separate for the time aspects of the *Performance Requirement* and does not represent the actual production timescales. The *Time Requirement* is conventionally dominated by the lead-time: the time taken from completion of the order to the delivery of the operational system. Lead-time is the time taken for the system to be operationally available and is itself generally governed by the lead-times associated with the individual and specific equipment modules.

5.1.5 Primary Reconfiguration Priorities

During the specification of a new system configuration, the customer will want to have the ‘best’ solution. However, the term ‘best’ is subjective and generally can only be determined by the consideration of the customer’s priorities. The priorities for reconfiguration can be divided into five categories: *Cost*, *Performance*, *Reconfiguration Time*, *Risk* and *Efficiency*.

The *Cost Priority* reflects the customer’s flexibility with respect to the cost requirement. If the cost priority is high, then the budget set cannot be increased. If the cost priority is low then the budget can be changed. A middle priority value means that the budget can be changed, but only with strong justification.

The *Performance Priority* represents the customer's flexibility with respect to the identified performance requirement indicator. The implication of the priority ranking is similar to that for the cost priority: if the priority is ranked highly then the performance requirement cannot be altered, if the ranking is low then it can be altered and a middle ranking requires a strong justification for change.

The *Reconfiguration Time Priority* is considered within the 3-Dimensional tool as it is linked only to RAS. It represents the customer's flexibility with regards to the time taken to complete each reconfiguration. Again, as with the two previous priorities, the ranking directly correlates to the customer's willingness for the requirement to be altered.

The three preceding priorities are all directly related to the specific similarly-named requirements. Therefore, the priority ranking indicates the flexibility within the specified requirement. The following priorities however, are not requirements plotted within the tool. Their ranking impacts the recommendations made and the strategy applied subsequent to the tools use.

The *Risk Priority* represents the level of risk that the customer is willing to accept. A high ranking equates to the need to minimise risk, whilst a low ranking indicates an acceptance of risk. This priority is linked to the innovation boundaries that are described below. A strong risk-aversion would mean that the solutions should be of a 'standard' nature; i.e. using standard technologies, processes and approaches, with which the system integrator has had prior experience. An acceptance of risk would result in potentially innovative and unusual solutions being investigated with the aim of finding a 'better' solution than would be available within the standard solutions.

The *Efficiency Priority* represents the customer's desire for the solution to be optimised for the product. This specifically relates to the type and number of new modules brought into the system. A high efficiency priority ranking represents the customer's need/desire for the solution to be optimised to delivering the product efficiently (this would generally be the case for larger production runs). A low ranking indicates that the absolute efficiency of the system is not of high importance. There is a potential correlation between η

and P, but the former is more specific and is representative of a constant factor whereas the latter is more flexible.

An important consideration is that, at this stage of the CAMARA approach, the requirements and prioritisations are not final or committal. They are selected in order to forecast and project their implications. Should the result not be suitable, the requirements and the priorities can be changed to alter the result.

5.1.6 Description of the Requirement-Priority Space Tool

Before the reconfiguration strategy can be determined, consideration of both the requirements and the priorities is needed to determine whether or not they are likely to result in a successful and suitable solution. Should this not be the case, then guidance is needed in the alteration of the requirements to ensure such a solution will be delivered.

For this purpose, a *Requirement-Priority Tool* is proposed. This tool provides a plot area representing the requirements. It includes boundaries within the plot area to represent the nature of the likely assembly system/configuration solution. When the requirements for each application are plotted and the solution nature identified, the priorities can be used to, where necessary, recommend the optimum approach for altering the requirements as well as providing the basis for the reconfiguration strategy.

The tool comprises two variants of the tool: the 2-Dimensional and the 3-Dimensional. The number of dimensions refers to the axes on the graph, which represent the requirements considered. The 2-D Graph is intended for implementation in cases where timeframes are not important and so do not feature as a main requirement. The addition of a third requirement to the graph results in a three-dimensional plot area. This substantially increases the complexity of the analysis and leads to a 3-D Priority Space Graph.

The major problem with the combination of the three requirements into a single plot space is that the interactions and relationships between the requirements are very different. Whilst a single plot area is possible, it is not realistically feasible.

The ultimate conclusion is that inclusion of a third axis increases the complexity of use and the volume of data required to deliver a useful plot area and curves. The proposal is for a modified 2-D approach, whereby the T_R requirement is considered as a major influencer of the reconfiguration strategy.

The consideration of the Reconfiguration Time is to be made by the implementation of a multi-solution projection approach. This approach utilises the Three Capability Lists produced by the Capability Model. The Compatible Capability Set effectively sets the boundary conditions for reconfiguration (where the proposed configurations are bounded by 'sensible' limits for the relevant application and situation and not by the extremes of what is possible). This leads to the proposal for consideration of Maximum, Minimum and Mean Configurations.

5.1.7 System Reconfiguration Range Projection

As described in Section 4.3.3.2, three configurations (R_{MAX}, R_{MIN} and R_{MEAN}) are considered; these are used to give boundaries and an approximate curve to any graphs which are plotted based on the performance/cost prediction. These configurations are defined by Section 4.3.3.3.

The motivation for these tools is to assist in the decision-making process regarding what degree of reconfiguration should be focussed on. The **degree of configuration** is not the same as the three levels of reconfiguration described earlier: it is better described as *the range of possible reconfigurations into which the most effective and efficient solution for this problem is found*.

5.1.8 Strategies and Implications for Reconfiguration of Systems

The value ascribed to each of the priority factors determines the possible strategies for requirement alteration and for reconfiguration. An important step in the reconfiguration planning is the determination of the requirements and their priorities and an evaluation of the likely impact on the potential solutions. If the *Priority Space Tool* has highlighted that a change in requirements is necessary, then that change will be affected by the priority values. The implications of this are summarised in Table 5-2

Table 5-2: Summary of the Requirement Alterations related to the priority rankings

Priority	Value	Implication to Requirement Alteration
Cost (κ)	High	Budget cannot be increased
	Medium	Budget can be increased if essential
	Low	Budget can be increased
Performance (P)	High	KPI cannot be reduced
	Medium	KPI can be reduced if essential
	Low	KPI can be reduced
Reconfiguration Time (T_R)	High	Reconfiguration Time must be minimised
	Medium	Reconfiguration Time should be restricted
	Low	Reconfiguration Time is not important
Efficiency (η)	High	Efficiency must be maximised
	Medium	Efficiency should be promoted
	Low	Efficiency is not important
Risk (R)	High	Risk must be minimised
	Medium	Risk should be restricted
	Low	Risk is not important

There are a limited number of controllable aspects of a configuration at the early stages of planning – this leads to only a few realisable stratagems, which are summarised in Table 5-3. One of the key factors that can be altered and controlled at an early stage of configuration planning is the *Process:Module Ratio* (PMR). The PMR represents the average number of processes delivered by each module within the configuration. It is found by:

$$PMR = \frac{\textit{Total number of processes from the PFD for the configuration}}{\textit{Total number of equipment modules in the configuration}}$$

In general terms, by reducing the value of the PMR each module has less to do and so cycle time is reduced. However, it also means that more modules are required and so system cost increases. This is a manifestation of the Efficiency priority and thus the target and flexibility of this value are determined by it.

Table 5-3: Summary of the Reconfiguration Strategies related to the priority rankings

Priority	Value	Implication to Reconfiguration Strategy
Cost (κ)	High	▪Maximise equipment re-use. ▪Increase PMR. ▪Minimise cost of procured modules.
	Medium	▪As per 'High', but without impact to other priorities.
	Low	▪Select equipment based on other factors
Performance (P)	High	▪Select optimal equipment modules for each process.
	Medium	▪Select optimal equipment modules for each process without impact to other priorities.
	Low	▪Select equipment based on other factors
Reconfiguration Time (T_R)	High	▪Maximise equipment re-use. ▪Utilise 'familiar' equipment modules.
	Medium	▪As per 'High', but without impact to other priorities.
	Low	▪Select equipment based on other factors
Efficiency (η)	High	▪Minimise PMR.
	Medium	▪Minimise PMR without impact to other priorities.
	Low	▪Select equipment based on other factors
Risk (R)	High	▪Alter requirements (if necessary) so that the Priority Space plot falls within the 'Central Region'
	Medium	▪Alter requirements (if necessary) so that the Priority Space plot falls within the 'Innovation Boundaries'
	Low	▪Select equipment based on other factors

5.1.9 Scoring of Primary Reconfiguration Priorities

The proposal is for a scoring system to be implemented in order to restrict the customer from prioritising everything as "High" and thus offering no flexibility with regards to the requirements of the solution. This system, termed the *Priority Scoring*, would work on the principle that the ranking of each priority incurs a score of 0, 1 or 2 for Low, Medium and High respectively. The selection of each priority leads to an aggregate score. This aggregate score will highlight the overall flexibility of the scenario:

- 0-4 – high flexibility, good chance of a solution being found.
- 5-7 – some flexibility, a fair chance of a solution being found.
- 8-10 – low flexibility, low chance of a solution being found.

It would be thus proposed that the customer be restricted to a priority score of 6, giving a good to fair chance of a solution being found.

There are a total of 243 possible combinations of Priority Score (as a result of 3^5) and so it is conceivable that a specific reconfiguration scenario be created for each one, thus creating a full *Reconfiguration Scenario Database*. However, completing this is outside of the scope of this research, instead a number of specific cases are highlighted as most probable and relevant to this work and these are detailed further.

5.2 Description of the Reconfiguration Scenarios Concept

In order to extract the full benefits from the model, the user will select one of the listed scenarios as the most applicable, and then be able to personalise aspects of it; creating their own personal scenario. The selection of a scenario will be through either manual consideration of the full Reconfiguration Scenario Database or through the use of the *Priority Scoring* detailed in Section 5.1.9.

The customisation and specification of the scenario will take on a similar form to that of the capability definition. The user will select one option from a list, each option leads to a new criteria to select. There is a finite list of possible outcomes and so the most relevant scenario can be applied. As a broad outline to the scenarios:

- If investment cost is the priority then minimise new equipment.
- If cost per unit is priority then optimise value of [Operational Costs / Output Volume]
- If cycle time / output is priority the aim to have one equipment module per required capability.
- If downtime is priority, then minimise reconfiguration (not just new equipment, but also moving of existing equipment).

Scenarios are the conditions in which a reconfiguration may be required. By selecting one of the defined Reconfiguration Scenarios, it should then be possible to specify the project with only a few further quantified details (such as exact production volume etc.) The Scenarios encapsulate the reasons for the reconfiguration and the situation in which it will occur.

5.2.1 Key Factors Affecting Reconfiguration Scenarios

The primary purpose of the Reconfiguration Scenario is to enable the user to formulate a reasonable set of requirements quickly when no specifics are known. This fits within the overall theme of providing a ‘quick-view’ of the potential solutions and their impact. It is envisaged that each user develop a customised portfolio of scenarios to suit their particular working environment, industrial area and product type. However, this thesis presents and uses the scenario based around the perceived primary role of CAMARA.

RAS are most likely to be implemented for the assembly of high-value, high-complexity, low-volume products. These products have what are traditionally conflicting requirements: systems that deliver very high yields (due to the cost implications of scrapping the products) but that also have low initial and operational costs (due to the short pay-back period associated with low production volumes) and short lead-times (as the acceleration of the time-to-market is required to maximise the benefits from production). Whilst certain high-value bespoke items can command a premium at the point of sale, this is rarely the case for assembled devices: the most notable exception being high-end watches[6]. These key factors affecting the Reconfiguration Scenarios are yield, cost, lead-time and equipment selection.

5.2.1.1 Yield

A system with a high yield is one in which the failure or rejection rate is very low. In reality, the very short runs associated with the products considered in this thesis will mean that rather than implementing specific and separate techniques, the minimisation of failure rates will be expected, thereby maximising yield with the cost of failures being included as part of the system cost. This is, whilst not a perfect situation, a more appropriate one as the major need is to ensure that the product batch is delivered as quickly and cost efficiently as possible – the delays and additional costs of full quality evaluation, implementation and adaptation are almost certain to outweigh the potential benefits.

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[6] Certain watchmakers command very high prices precisely because the items are limited in production. However, one of the other key selling points is that the watches are also handmade. The implementation of RASs would remove this and thus detrimentally affect sales. This is not the case for products with purely functional purposes.

From this, it can be concluded that the assembly systems that produce high-value, high-complexity, low-volume products will need to focus on an approach that maximises overall yield. The requirement for a high yield will mean that the reconfigured system should be designed with process quality as a key factor. However, the implementation of extensive and complex quality control, beyond ensuring that products are fit-for-purpose, are unlikely to be included. This is primarily due to the second, and conflicting, requirement: Cost minimisation.

5.2.1.2 Cost Minimisation

A system with minimised cost is one in which all of the costs are restricted to the point where any further reduction would detrimentally impact the system performance to below the acceptable limits. Within the context of this research, which does not explore costs, it is assumed that there is a direct link between the effort required to reconfigure and the cost of reconfiguration.

Therefore, the minimisation of the total configuration cost is achieved when each of the constituent elements is minimised. Minimisation in this case cannot be the absolute removal of cost, as the configuration must still meet certain performance criteria, so ‘minimisation’ is to be achieved within reason.

The implementation of RAS has an impact in reducing the integration costs by reducing both the design and integration effort. Further to this, there will be little hardware adaptation of the system needed. The remaining costs are all directly attributed to the processes and equipment selected to meet the required capabilities. The result of this is that the selection of the module type, and then of the exact model, has a major impact and importance in the effectiveness of the configuration.

5.2.1.3 Minimisation of Lead-time

One of the key factors affecting the success of an assembly project is the lead-time associated with it. Lead-time can be used to refer to a number of different time frames. Typically, it is used to refer to the time taken to acquire an item from the point at which the order is placed and this broad definition can still be used within this thesis.

Lead-time is calculated as the time between placing an order for something and its receipt. In a dynamic environment, this time can be prohibitive in the realisation of system reconfiguration and thus response to change. Thus it is proposed in Section 4.3.1.1 that the focus of reconfiguration should be with modules that are currently available. This work does not extend to integrtion within the over-arching procurement and servicing systems implemented within a company

The concept of system-to-service transformation has been described in Chapter 3; the paradigm results in *suppliers no longer ordering a system to produce the product but rather procuring the service of supplying them*. Therefore, lead-time no longer refers to the time between ordering and receipt of the system, but instead the receipt of the products. The primary role of RASs in delivering batches of products rather than continuous mass production[7] compounds further supports this definition.

5.2.1.4 Optimisation of Equipment Module and Model Selection

For each individual analysis performed, both the products and the system architecture are assumed to be fixed and defined. For the effectiveness and efficiency of CAMARA, variations in product and/or system architecture are considered in separate analyses. Identifying a number of unknowns with two or more variables will become an overly complex computational problem.

Whilst it has been established that over-specifying a module is uneconomic there is the potential that under-specifying may yield cost benefits that outweigh the performance reduction, though this does not apply should this cause the product to be itself below standard and unacceptable. The most relevant application for this is in the speed of the processing. By reducing process speed, cycle time is increased which increases the lead-time for the customer’s receipt of the products. However, it also reduces the configuration cost and so, provided the delays are sustainable, could be financially beneficial. Such projections are an important feature of identifying and defining reconfiguration options early in the product design phases.

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[7] As highlighted earlier in this thesis, RASs are primarily focussed on delivering batches of products: the benefits of such systems are minimal if implemented in a system which is expected to have a single production purpose for the foreseeable future.

5.2.2 Reconfiguration Scenario Description

The manufacturer of any product has the primary purpose of, and concern with, profitability. Profitability is the mechanism by which organisations make money, which is the ultimate aim of the business. Profitability is one of the key measures of success of a manufacturing project, but it is not the only measure. During the stages of product development prior to the final mass production, simply delivering the products within tolerance (where tolerances govern time, quality and resources, as well as geometries and performance) is the marker for success. The success or otherwise of a product is not born from a single aspect but rather the balancing of a number of different, and often conflicting, factors.

5.2.2.1 Primary Reconfiguration Scenario Details

The previous sections have identified and described the major considerations within the primary *Reconfiguration Scenario*. This section will describe the details and implications of that scenario.

The Primary Reconfiguration Scenario is based upon the situation proposed in Section 3.5. In this case, the manufacturer has three main concerns: lead-time, profitability and the primary objective of delivering the product batches on time. Table 5-4 summarises the Priority Score for the Primary Reconfiguration Scenario and the resulting implications. The scores indicated in these scenarios is subjective to the person entering them: the restriction to three levels is intended to eliminate this as far as possible so that consistent assessment of situations is provided by multiple users.

Table 5-4: Summary of the Primary Reconfiguration Scenario

Priority	**Score**
Cost	2 (High)
Performance	0 (Low)
Reconfiguration Time	2 (High)
Efficiency	1 (Med)
Risk	1 (Med)
Total Score = 6	

The combined implications of the Primary Reconfiguration Scenario for the Requirements alteration is:

- Budget cannot be increased.
- Performance is not important.
- Reconfiguration Time must be minimised.
- Efficiency should be promoted.
- Risk should be restricted.

The combined implications of the Primary Reconfiguration Scenario for the Reconfiguration Strategy is:

- Maximise equipment re-use.
- Increase PMR.
- Minimise cost of procured modules.
- Select equipment modules that deliver processes for multiple products.
- Maximise equipment re-use.
- Utilise 'familiar' equipment modules.
- Minimise PMR without impact to other priorities.
- Alter requirements (if necessary) so that the Priority Space plot falls within the 'Innovation Boundaries'.

It should be noted that these priorities lead to some conflicting suggestions for appropriate action: the minimisation of cost requires the number of modules to be minimised, however the maintaining of efficiency requires the opposite. This is discussed in detail in Section 5.3.1.

5.3 Strategies for System Configuration Optimisation

With the Capability Lists produced by the Capability Model and the Reconfiguration Scenario identified, the next step is to determine the details of each configuration.

This begins with an evaluation of each individual configuration (i.e. the solution for each product), validation of each configuration, evaluation of the total system (i.e. all configurations combined) and then validation of the total system.

5.3.1 Individual Configuration Analysis

One means of defining the individual configurations has previously been outlined in Section 5.1.7: that of the Reconfiguration Range. The concept of the Maximum, Minimum and Mean configurations allows for the investigation of a broad range of solutions with relatively limited knowledge or predefined requirements. The *Reconfiguration Range Methodology* is described below.

There are 243 possible Reconfiguration Scenarios in terms of their requirement priorities. These can each be customised thus giving a potentially very large pool. Each of these scenarios would be best served by the creation of a specific configuration evaluation and optimisation strategy.

Broadly speaking, these strategies may not differ by a large amount, particularly when the priorities are similar. Furthermore, the strategic implications detailed in Section 5.1.8 give overall guidance as to the actions to be made.

It is not within the scope of this thesis to define all of the possible evaluation strategies. Instead, alongside the Reconfiguration Range method, two strategies will be defined and described. The first is based upon the Reconfiguration Scenario from Section 5.2.2.1 where the products are being prototyped. This method is termed the *Prototyping Methodology* and is described in Section 5.3.1.2. Whilst the second is based on the same scenario, the production volume has been altered to substantially larger batches. This method is termed the *Elimination Methodology* and is described in Section 5.3.1.3.

5.3.1.1 Description of the Reconfiguration Range Methodology

The core principle behind the *Reconfiguration Range Methodology* is that three potential solution configurations are generated for each product. As described previously in Sections 4.3.3.2 and 5.1.7:

- The Maximum Reconfiguration is where only the exact matching Existing Capabilities are retained. The remaining Required Capabilities are procured based on the lowest possible PMR.
- The Minimum Reconfiguration retains all Existing Capabilities with matches and procures only the minimum number of new modules (maximising the PMR) to satisfy the Required Capabilities.

- The Mean Reconfiguration is essentially the mid-point between these two extremes – the difference in the number of procured modules between the maximum and minimum configurations is approximately halved and arranged into a coherent configuration.

Each of these configurations is then pursued in parallel. They are investigated in much the same manner as solutions that are based on more specific requirements, however the process is somewhat shortened as there will not be an investigation into the requirements or priorities, nor will the configurations be optimised before performance projections.

In addition to considering the three configurations as representative of the range of options, depending on the priorities identified in a scenario, one of the above-defined configurations may in fact be optimal.

The *Maximum Reconfiguration* highly prioritises *Performance* and E*fficiency*, with C*ost* and R*econfiguration Time* ignored and *Risk* not automatically considered. However, the inclusion of a large number of new modules will incur some risk but this is opposed by the clear focus on performance and thus on production results: indicating a natural aversion to risk. Thus a potential Reconfiguration Scenario met by this configuration is shown in Table 5-5.

Table 5-5: Reconfiguration Scenario for the Maximum Reconfiguration as a stand-alone solution

Priority	**Score**
Cost	0 (Low)
Performance	2 (High)
Reconfiguration Time	0 (Low)
Efficiency	2 (High)
Risk	1 (Med)
Total Score = 5	

Table 5-6: Reconfiguration Scenario for the Minimum Reconfiguration as a stand-alone solution

Priority	**Score**
Cost	2 (High)
Performance	0 (Low)
Reconfiguration Time	2 (High)
Efficiency	0 (Low)
Risk	2 (High)
Total Score = 6	

Table 5-7: Reconfiguration Scenario for the Mean Reconfiguration as a stand-alone solution

Priority	**Score**
Cost	1 (Med)
Performance	1 (Med)
Reconfiguration Time	1 (Med)
Efficiency	1 (Med)
Risk	1 (Med)
Total Score = 5	

The *Minimum Reconfiguration* highly prioritises *Cost* and *Reconfiguration Time*, with *Performance* and *Efficiency* ignored and *Risk* not automatically considered. However, the focus on the use of existing (and therefore known and experienced) modules automatically reduces any potential risk to the configuration. Therefore, it is likely that the most relevant scenario would consider Risk to be a high priority. Thus a potential Reconfiguration Scenario met by this configuration is shown in Table 5-6.

The Mean Reconfiguration represents an often abstract mid-point between the minimum and maximum configurations. It can therefore be seen to be representative of a scenario whereby all of the priorities are given the same ranking, and such a scenario is shown in Table 5-7.

5.3.1.2 Description of the Prototyping Methodology

The Primary Reconfiguration Scenario, defined in Section 5.2.2.1, has priorities focussed on minimisation of cost and downtime. This is highly typical of the anticipated applications for RAS: for prototyping of trial products. Secondary considerations are towards maintaining good efficiency and reduction of risk. Thus, the application of the Minimum Configuration would be too simplified and not ensure some efficiency is retained. An example scenario for this methodology to be applied is shown in Table 5-8.

Table 5-8: The Reconfiguration Scenario for the Prototyping Methodology

Priority	**Score**
Cost	2 (High)
Performance	0 (Low)
Reconfiguration Time	2 (High)
Efficiency	1 (Med)
Risk	1 (Med)
Total Score = 6	

The similarity between this scenario and for the Minimum Scenario above can be seen, however key differences exist in the priorities for Efficiency and Risk, which have an impact on the methodology used to determine the configuration.

As with the Minimum Reconfiguration, in order to meet he Cost and Reconfiguration Time priorities, the existing equipment should be used as far as possible. Thus each of the Required Capabilities that matches an Existing Capability is allocated to the relevant module. This may result in one module delivering more than one production function.

There are two main reasons for the consideration of efficiency within a prototyping environment. The first is that prototyping precedes mass-production and, as highlighted in Section 3.5, realistic representation of the mass-production environment ensures more accurate results from the trials and tests that the prototype products are used for. The second is that within the context of this thesis, multiple products are considered for production and simultaneous delivery, hence the desire to ensure maximum efficiency, without substantial impact on cost.

The impact of this is that the Prototyping Methodology must strike a balance between minimising the cost of new modules, whilst keeping a reasonable level of efficiency. Here it is thus defined that each module can only deliver (in the final configuration) a maximum of two capabilities of the same class. This means that whilst a single module can perform several time-sequential capabilities, it can only deliver a limited number of parallel ones, thereby ensuring efficiency is not very low whilst still enabling multi-role modules to be used to keep costs low.

5.3.1.3 Description and Demonstration of the Elimination Methodology

In a situation that is similar to the one described in Section 3.5, the priorities are somewhat mixed. There is the need to minimise cost and the reconfiguration effort, but also to try to produce the parts efficiently with minimal disruption during reconfigurations. Such a scenario is exemplified in Table 5-9. The similarities to the Mean configuration can be seen; there is no clear dominance of one priority type. This is foreseen as a common scenario as most customers will be unclear as to the impact of their prioritisations and indeed may well not know what their priorities are.

The *Elimination Methodology*, described in Section 5.3.1.3 and Appendix B, is used to find an efficient configuration solution that uses as many *Existing Capabilities* as possible to deliver the *Required Capabilities*, whilst maintaining a PMR as close to ‘1’ as possible. This approach is foreseen to be one of the more common applications as it seeks to strike a balance between absolute efficiency of the solution and maximised equipment re-use. The methodology is described below through the application of a simplified example. This example is based around a selection of capabilities – the exact details are not relevant to the illustration of the process.

The Comparison Matrix is populated during the Capability Modelling phase and as a result the *three Capability Lists* are generated. These are *Surplus Capabilities* (C_{SP}), *Procured Capabilities* (C_{PR}) and *Consideration Capabilities* (C_{CN}).

Table 5-9: The Reconfiguration Scenario for the Elimination Methodology

Priority	**Score**
Cost	2 (High)
Performance	0 (Low)
Reconfiguration Time	1 (Med)
Efficiency	1 (Med)
Risk	1 (Med)
Total Score = 5	

5.3.2 Individual Configuration Validation

There are two key types of validation linked to the equipment modules:

1. Module removal validation. Before a module is confirmed for removal, it must be checked whether or not it has another role within any of the configurations. If it does, then it may be reconfigured out of one configuration, but will not be removed for the complete system.
2. Module acquisition validation. During the procurement of new modules, each capability is searched through the new equipment database to find a suitable match, however there may already be a match in the existing modules.

Point 1 is covered by the provision of the combined comparison matrix that ensures only modules with a ‘true’ zero value are removed. Point 2 is covered by searching existing modules *before* searching the equipment library for matches to required capabilities.

The three Capability Lists generated previously for each product must be validated with respect to the equipment modules that will deliver them. In the case of the Surplus Capabilities, it is important to ensure that the removal of the relevant equipment modules will not result in a loss of required capability. For the capabilities that are satisfied, it will be necessary to assess the relevant Equipment Modules based upon criteria determined by the Reconfiguration Scenario. For the Procure Capabilities, appropriate Equipment Modules must be selected to meet the requirements. The result of this will be a new configuration of equipment modules with a number of Capabilities able to deliver the relevant capability set for a particular product. This new configuration, including the compatibilities and designations, is logged in a *Configuration Table*. A set of Configuration Tables will be produced, one for each product.

Each configuration has been defined in terms of the Capabilities that must be delivered. In order to realize the working configuration in the factory, it is necessary to allocate equipment modules to each of the Capabilities. In the case of the Procure Capabilities, it will be necessary to identify the equipment modules from the marketplace that best meet the needs both of the Capability, the system and of the project overall. The Reconfiguration Scenario will impact the selection criteria, but not the process.

5.3.3 Total System Evaluation

Whilst it is important to ensure that each configuration meets the technical needs of the customer (specifically in relation to the product required), there are several factors that are best considered through the evaluation of the complete system, i.e. that which is required for all of the products. Evaluation at this level moves beyond conventional types of line balancing and similar configuration refinement techniques and into costings and logistics.

Cost reduction can be potentially achieved through consideration of all of the configurations. The total cost can be found by summing the cost of the new modules and the integration effort required to add them. However, this cost can be reduced through the application of a *Cost Reduction Approach*. This approach looks to reduce cost by reducing and overlapping modules.

Another key consideration is that of the sequence in which the different products are produced, through the Production Sequence Analysis, which has the primary aim of minimising the reconfiguration effort across all of the configurations.

5.3.3.1 Description of the Cost Reduction Approach

Each configuration has been defined, thus giving a complete list of modules to procure and integrate, and therefore the basic system cost can be calculated. However, in scenarios where he *Cost* priority is given a *High* value, it is necessary to try to reduce this cost. As this issue is not a primary consideration within the Reconfiguration Scenarios dealt with in this thesis the approach will only be described in generalised terms and detail.

This is achieved by:

- *Requirement Review*: reviewing the technical requirements and reducing the ‘expensive’ ones, i.e. accuracy.
- *Module Combination*: providing several required capabilities with one module.

Requirement Review offers a comparatively simple means of reducing cost. The requirements are reconsidered with the knowledge that the result is a system that is too expensive, with ‘problematic capabilities’ highlighted by the System Integrator. If these requirements can be changed then the module allocation can be re-performed to find the new cost. By reducing the complexity of the required operations, the necessary modules should be cheaper.

The benefit of this approach is that it offers the potential for significant savings without major changes to the configuration, but it may require that the product designs be changed – the impact of this will be dependant on the design flexibility. However, it should be noted that any changes to components, particularly with respect to the integration of functions, is likely to result in an increase in complexity and, subsequently, cost – such considerations are outside the scope of this work.

Module Combination offers a means of reducing cost be allocating fewer modules to the configurations. The new modules have already been validated to ensure there are no obvious overlaps. Instead, the approach considers the acquisition of more complex (and hence likely more expensive) modules to provide multiple required capabilities. There is a possibility that this additional complexity negates or even supersedes any potential benefits yielded – this requires additional investigation and specific consideration of the individual modules in question and requires a complex searching of the equipment library via an algorithm that is briefly described below.

The key objective of the *Module Combination Algorithm* is to minimise the cost of a complete system (i.e. all configurations). This is achieved by investigating the cost savings achievable through the minimisation of the number of modules required to deliver the required functionality. The proposed algorithm is to be based around a complex searching function. The input to this is the complete list of *Required Capabilities* that are to be procured; these are then used as the search parameters within the *Equipment Library*. The starting point is to find one module able to deliver all of the capabilities, if there is no single module then the search is for a two module combination and so on until the final solution which is the allocation of one module to one capability.

Depending on the processing power and time available, every possible combination could be found, the initial cost calculated (as that information is contained within the library) and the solutions ranked with the lowest cost as rank 1.

5.3.4 Minimising Reconfiguration Effort via Production Sequencing

At this point in the analysis, each product has an optimised solution configuration. However, there are still a number of decisions to be made and issues to be resolved, specifically finding the *Production Sequence*. This is the order in which each of the products is produced and is one of the most critical decisions affecting the performance and efficiency of the system. It is generally preferable to minimize the system disruption, downtime and reconfiguration effort (module exchange), thereby minimising the overall cost of reconfiguration. This is achieved through adopting a ‘product-centered’ approach and identifying the commonalities between each of the products. The *Production Sequencing Method* is detailed below:

The original *Comparison Matrix* is used; the correlation matrix segment (the triangular elements at the top of the Comparison Matrix) enables comparison between the Required Capabilities for the different products. As with the previous comparison process, a ‘1’ is entered if the Capabilities are compatible, ‘0’ is entered for non-matches and no entry is made where the capabilities are of different classes. It is worth noting that, in this case, there is no structured dominance of one product over another – *direction is irrelevant*. Thus it does not matter which of the Capabilities are more complex – the question is essentially "can both of these required capabilities be delivered by one equipment capability?"

The *Product Correlation Ratio* (PCR) is then calculated for each of the relationships. The PCR is a number which represents how compatible the two products are from a capability perspective. It is calculated by then number of compatible Capabilities over the number of comparisons made (i.e. dividing the number of '1's by the number of '1's and the number of '0's). This calculation only considers the actual comparisons so that a PCR of 1 is achievable. The PCRs are logged with the relationship in a table in the first column, with descending PCR values. The table also shows the list of products, in no particular order, along the top row. The second row gives the sum of the PCRs for that product. The central elements of the table are used to indicate which products are associated with each PCR. The PCRs are designated with the letters of the appropriate products, e.g. PCR_{AB}. A log is used to keep track of which products have been allocated in the sequence.

It is desirable to use the relationships which have the highest possible PCRs and can provide an uninterrupted sequence of reconfigurations. There are a number of products and a larger number of relationships between them. , so:

$$k = [j * i] / 2$$

where;

i = the number of PCRs needed to make a complete production sequence

j = the number of products considered

$i = j - 1$

k = the total number of relationships

It is not possible to simply select the i highest PCRs, as this may well not include all of the products. Where j>3, the selection process for the i PCRs must ensure that the i highest PCRs *that form a coherent sequence involving all j products.*

The resulting list of relationships will offer two sequences; one the reverse of the other. The selection between these will be on the basis of the first reconfiguration effort. This is evaluated by finding the number of equipment module exchanges required for each configuration. The configurations for the two relevant products are compared to the existing system. For each, the number of modules to be procured is added to the number of modules to be removed. The higher the number, the more effort required in reconfiguring. Therefore the configuration with the lowest score is selected as the starting point. With the Production Sequence defined, the final step in this phase is to detail the System Configuration Lifecycle. This is populated by collating the relevant lists of modules for each stage; for both the individual configurations (the list of modules needed to produce the product) and for the reconfigurations (which consists of modules to be removed and added).

5.3.5 Specification of Assembly Systems

The primary role of the approach is to evaluate the relevant challenge and scenario at a capability level in order to identify solutions that have not been influenced or prejudiced by assumptions of requirements and abilities. However, it is also important to enable the realisation of the proposed configuration solutions and this requires the consideration of factors beyond the abstract concept of capabilities.

Current practises in assembly system specification are based on a single trade-off: the set of product requirements must be delivered by a solution with the best possible combination (for the particular application) of financial cost, lead time and performance. These three factors cover a wide range of interconnecting, and sometimes overlapping, points and issues. The relationships are complex and generally non-linear, however some general rules can be extracted:

- As cost increases, performance increases and vice versa.
- Reducing lead time will reduce performance, increase cost or both.

This trade-off is the major consideration for assembly system specification. When considering the reconfiguration of an existing system for a new purpose, the number of factors, and therefore the complexity, increases. The trade-off remains the same, however the new factors must account for the use of the existing equipment – even at a simple level the existing equipment presents additional considerations:

- Maximising equipment re-use is potentially the cheapest and quickest, but may not offer the best performance.
- Completely redesigning the system will likely give the best performance, but at the highest cost and with the longest downtime.

These considerations are already becoming complex for an engineer to accurately assess, let alone predict the outcomes of each option. The situation is made more complex when considering limited batch production or other specific project requirements.

It is therefore clear that the additional complexity presented by multiple products, and thus multiple configurations, becomes almost impossible to deal with without a structured and defined process.

5.3.5.1 Equipment Validation

Whilst the specification of the capabilities of each equipment module should prevent the mis-allocation of equipment, it is sensible to ensure that available equipment models can meet the generic equipment modules. In fact, this review is more specifically to ensure that the specific equipment models required do not substantially alter the initial budget estimates. Furthermore, it is proposed that the CAMARA operator review the existing solution for inconsistencies.

Therefore an important element within the methodology is to ensure that the removal of the C_{SP} list does not impact upon the C_{MT} or C_{CN} lists. For the most part this is assured by the method of module allocation and the definition from the taxonomy that one module can have only one capability. Furthermore, this is not a problem across several configurations as the removal of a module from one configuration does not remove it from overall availability. This is covered in the System Configuration Lifecycle planning in Section 5.3.5.4.

However, the major concern is the *Emergent Capabilities*. These are the capabilities that only exist through the combined application of multiple equipment modules. These are considered within the Comparison Matrix as capabilities in their own right, thus by declaring these as ‘surplus’ and removing the associated modules at least two additional capabilities will be lost.

It is thus essential to ensure that the removal of the modules associated with the C_{SP} does not remove any C_{MT} or C_{CN}. This is intended to be achieved through the implementation of the links between capabilities and equipment modules at the definition level. This would ideally be supported by automation of the Comparison Matrix.

The validation method is thus:

1. Identify the module(s) associated with each capability in the C_{SP} list.
2. From this list of modules, highlight those with, or that are, *Emergent Capabilities*. The remaining modules are marked for removal for that configuration.
3. Each highlighted module is checked:
    a. if all of the associated capabilities are surplus then the module is also marked for removal from the configuration,
    b. if one or more of the capabilities are needed, then the module is marked for retention for the configuration.

This information is utilised by the Module Allocation and System Configuration Lifecycle planning phases.

5.3.5.2 Module Allocation

The process of allocating modules to the configuration is largely guided by the previously-defined priorities. This supports the decision regarding the PMR, which is central to this process – the specification of specific equipment models comes later. In order to control the PMR, the capabilities need to be clustered into groups that are delivered by a single module, with the modules themselves then clustered into workstations. The target of this element of the work is to generate a schematic layout of the modules, an example of which is shown in Figure 5-1.

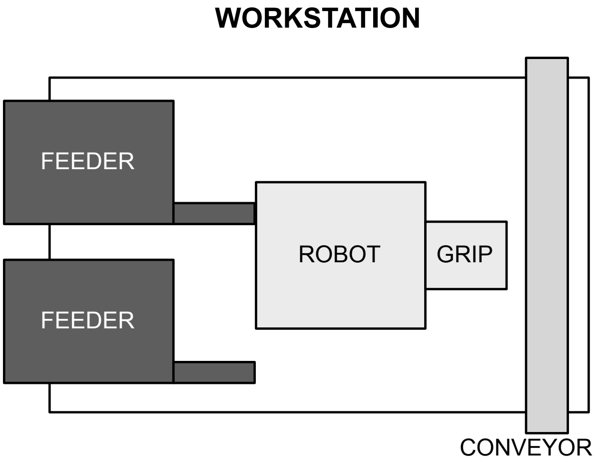


Figure 5-1: An example of a schematic module layout diagram

5.3.5.2.1 Module allocation for minimising PMR

At one end of the scale, where the PMR is minimised, module allocation is based upon identifying one module for each C_{RQ}. In this case the PFD that is described in Section 4.3.1.2 provides the basis for a schematic module layout. Each capability is transformed into a module or, in the case of *Emergent Capabilities*, group of modules. This process is illustrated in Figure 5-2.

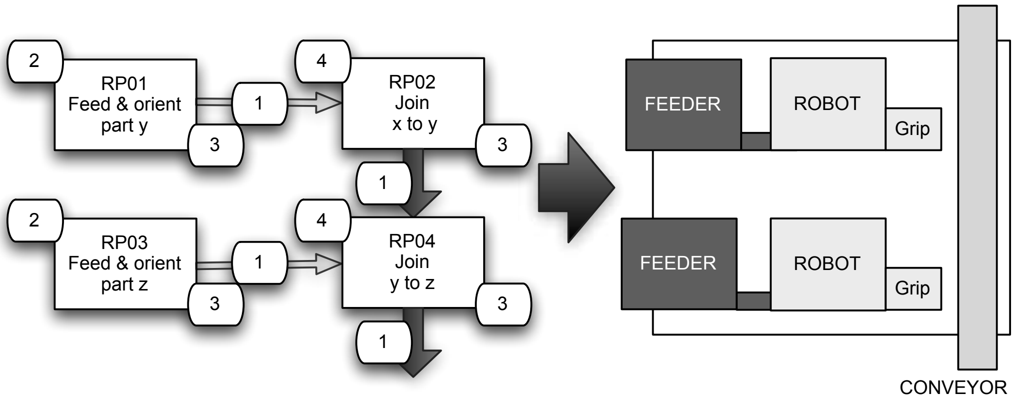


Figure 5-2: Illustration of the conversion of the CFD into a schematic module layout diagram for the case of PMR minimisation

5.3.5.2.2 Module allocation for maximising PMR

At the opposite end of the scale, where the desire is to maximise PMR (due to the need to minimise other factors, such as Cost and/or Reconfiguration Time), the module allocation process is based upon identifying those modules able to deliver the most capabilities.

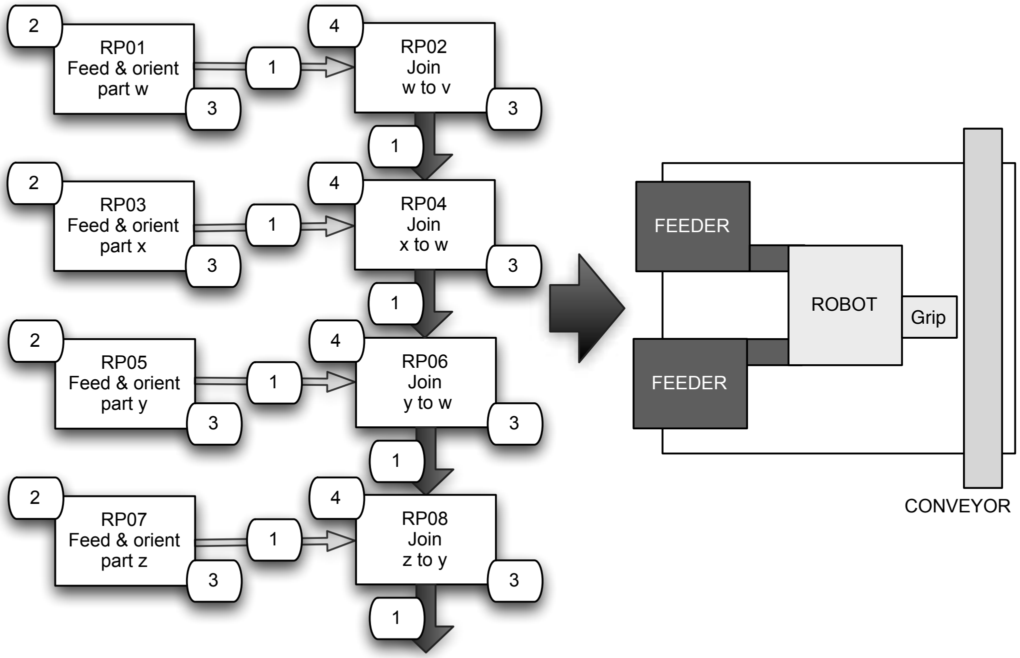


Figure 5-3: Illustration of an example of the module allocation process for maximising PMR

Without investigating the specifically available equipment modules, this process relies upon the clustering of processes according to their class. Thus, for the example illustrated in Figure 5-3, it is based upon the grouping of all of the capabilities of a certain class together and assigning them to a single module. Such an approach is idealised and assumes the availability of suitably flexible equipment. This will result in a single workstation with between two and six modules (assuming the complete taxonomy is used). In most cases, it is anticipated that the module allocation will exist somewhere between these two extremes.

5.3.5.3 Equipment Specification

The specification of the exact equipment to be used in each configuration is important in the final realisation of the proposed solutions. The process itself will require the population of the *Equipment Library* (see Section 6.2.6.1) with sufficient numbers of models to, at the very least, provide a realistic representation of the market.

This work will require that each of the models have the capabilities it provides be identified and then defined via the processes described in Sections

4.3.1.1 and 4.3.2 respectively. It is only with a sufficient level of detail and volume of data sets that appropriate specification can be made and these efforts are outside the scope of this thesis.

5.3.5.4 System Configuration Lifecycle Projection

Once each of the configurations has been separately defined and specified, and the order of production confirmed, it is important to fully define each of the stages of the system's lifecycle. This will commence from the current state of the system and progress through each reconfiguration and operation stage until the final operational condition. This lifecycle projection can be made either with the fully specified equipment models or by considering only the allocated modules. For the purposes of this thesis, it will be assumed that the projection is based upon the allocated modules.

Decommissioning is not specifically considered as it is presumed that, as the system is of a RAS architecture, it will continue to be used beyond the end of the projected phase. Thus, the key considerations for lifecycle projection are:

1. The sequence of the operational configurations,
2. The modules to remove from the previous configuration,
3. The modules to add to the previous configuration.

These points need to also consider the differences between modules that are available but not part of the existing configuration (i.e. in *System Storage*) and the modules that must be procured; this also extends to the removal of modules as some may be needed for later configurations. Furthermore, some modules that are retained may need to be physically moved within the system. These decisions are represented in the flow diagram in Figure 5-4, whilst the reconfiguration process itself is represented schematically in Figure 5-5.

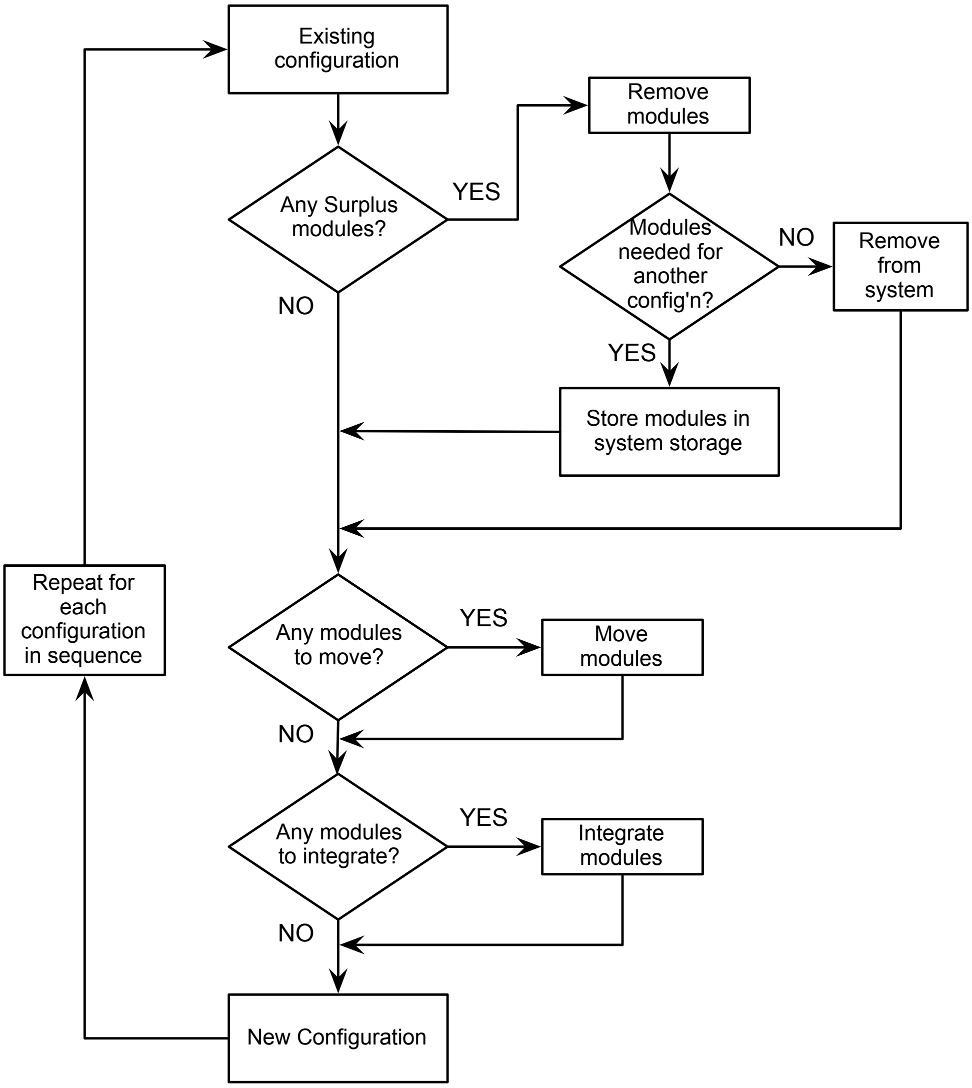


Figure 5-4: The flow diagram for identifying the module motion during reconfiguration

Once this process has been completed for each configuration, the results can be tabulated, an example is shown in Table 5-10 (which is based upon the schematic in Figure 5-5). This example is based around three configurations; one existing (*Configuration A*) and two new (*Configurations B* and *C*).

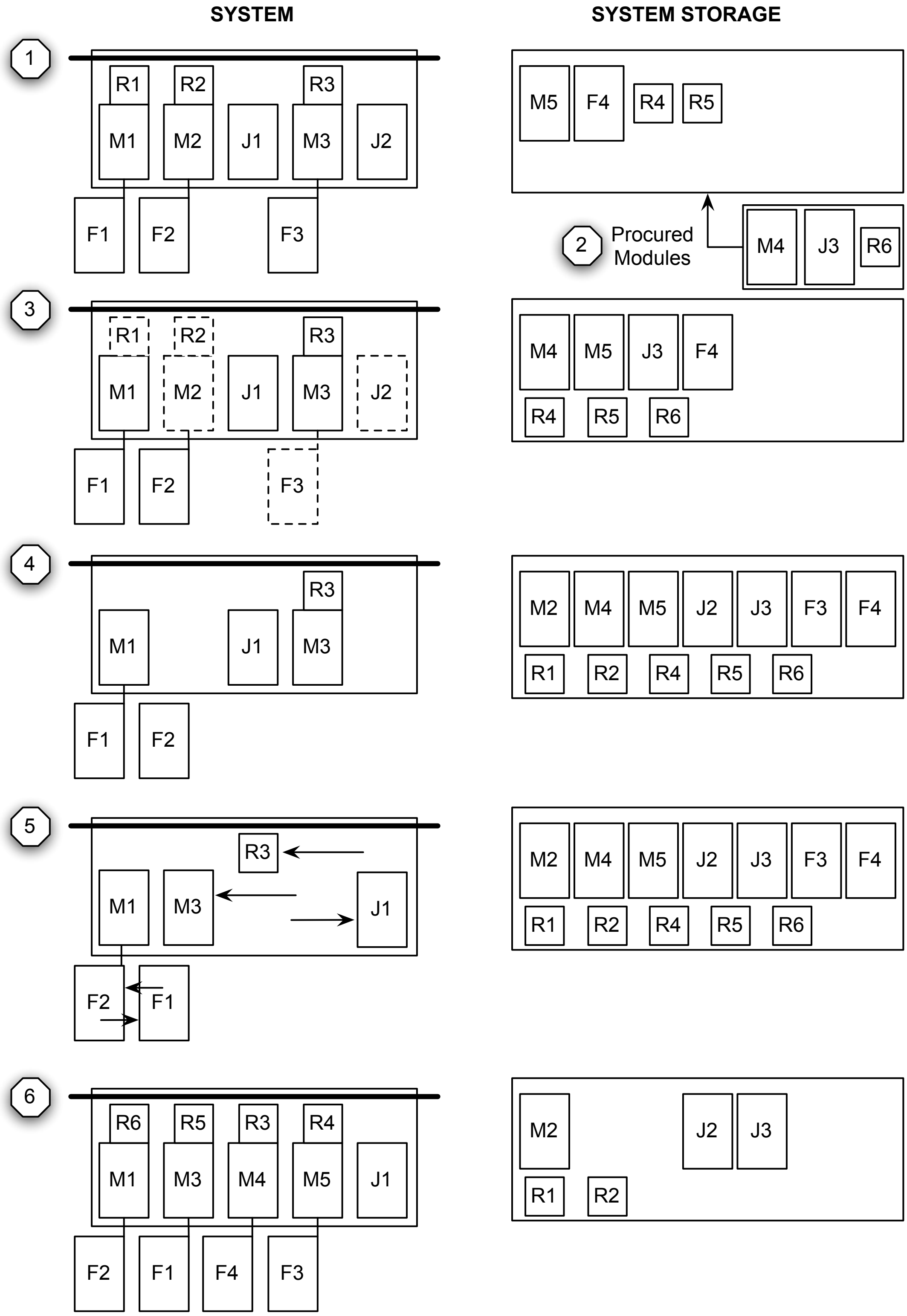


Figure 5-5: Schematic representation of the reconfiguration process

Table 5-10: Tabulation of the system configuration lifecycle, from example in Figure 5-5

Stage	Action	Relevant Modules
1	Stop production in *Config'n A*	N/A
2	Acquire all *Procure* modules for *Config'n B*	J3, M4, R6
3	Remove *Surplus* modules	F3, J2, M2, R1, R2
4	Store *Surplus* modules	F3, J2, M2, R1, R2
5	Move *Retained* modules	F1, F2, J1, M3, R3
6	Add *Required* modules	F3, F4, M4, M5, R4, R5, R6
7	Commence production in *Config'n B*	N/A

By tabulating this data, exporting to other external applications, such as procurement systems, project management and quotations are simplified. Connections to these systems are important for the users, primarily the System Integrator, to seamlessly move from conceptualisation, through evaluation and projections to realisation.

5.4 Summary

- The key motivations for the reconfiguration of an assembly system have been described.
- The main Reconfiguration Requirements and Priorities, from the customer's perspective, have been presented along with the Requirement-Priority Space Tool that aids in the clarification of the probabilities of appropriate solution configurations being generated.
- The Reconfiguration Scenario concept, which utilises the outputs from the Requirement-Priority Space Tool, has been presented.
- The use of the Boundary Configurations in projecting a reconfiguration range has been outlined.
- The Strategies for Optimisation of configurations and their associated implications have been described, with specific example strategies shown.
- The principles and implications of allocation and validation of generic equipment modules as well as of specific equipment models have been outlined.

- This Methodology is, by nature, data intensive. As a result, realising it within complex environments (where the greatest benefits will be realised) requires consideration of an automated implementation, which is outlined in Sections 6.4 and Appendix D.

6 Auxiliary Functions Supporting the Approach

The 3D-M project placed emphasis not only on the individual methods and approaches used and developed to deliver miniaturised and integrated products, but also the integration of the processes themselves together with the key enabling technologies. This Chapter reflects the work and investigations conducted into the integration and realisation of the CAMARA Tool and towards the 3D-M objectives.

6.1 Introduction

In order for the CAMARA Tool to be realised, it is necessary for a number of specific areas to be considered and developed, these being; *Communications*, *Microdevices*, *Assembly Equipment* and *Software*. These four enablers have different but intrinsic links to and roles within the integrated approach, as shown in Figure 6-1. This shows the inter-relationships between the Stakeholders as a central element. This is linked to both the Products and the Equipment and leads into the Requirements: this represents the most important facets of the Communication structure. This is followed by the Capability Model and reconfiguration Methodology, as described in Chapters 4 and 5 respectively.

Communication considers the issues associated with the availability of the required information and data, some of which is directly part of the construction of the CAMARA Tool itself. Rather than a focus on the ‘physical’ movement of data, this issue primarily concerns data acquisition; what data to acquire and from where to get it, as well as storage and the links from the data to the relevant elements within the CAMARA Tool. The elicitation of Requirements is also supported by their analysis and evaluation of the feasibility of realisation.

Microdevices must be designed and developed with particular consideration of the processes used to deliver them, whilst the *Assembly Equipment* used enables the processes. It is through the specific consideration of both devices and equipment that innovative and integrated processes can be developed. *Assembly Equipment* poses a significant challenge for the CAMARA Tool as it is necessary for modularity to be realised for the features and benefits to be supported sufficiently.

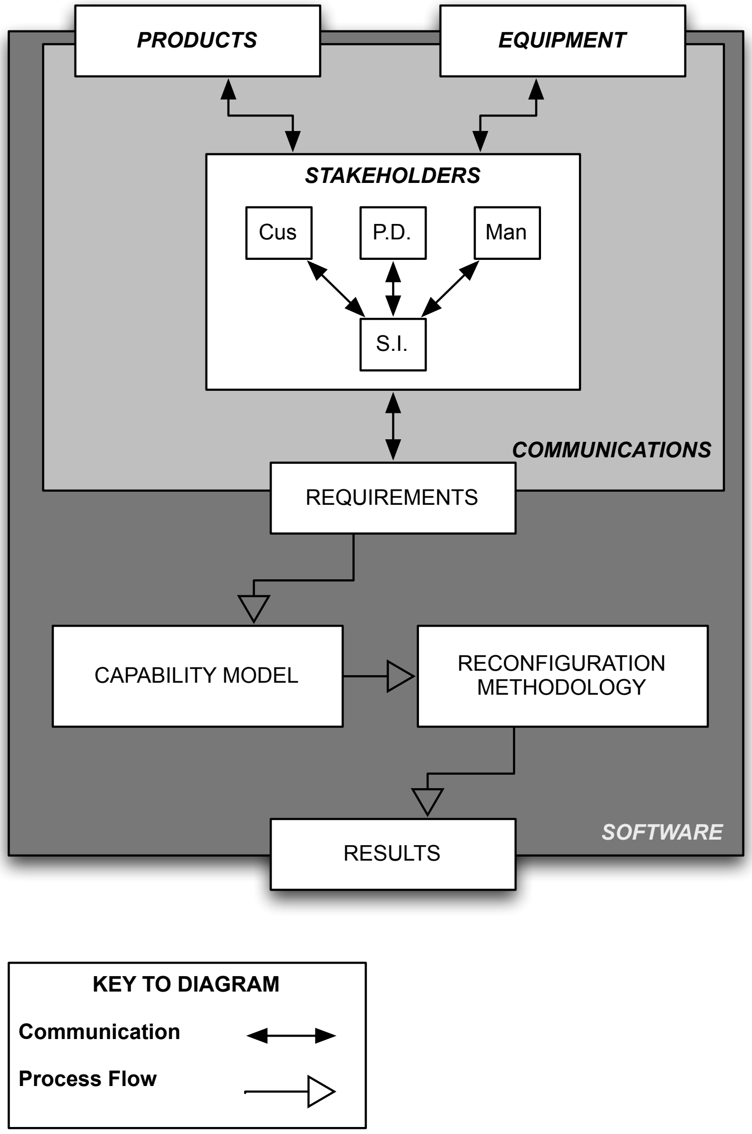


Figure 6-1: Representation of the links between the four enablers and the core of the CAMARA Tool.

Software is the preferred means of the CAMARA Tool being ultimately available and used. It is desirable to ensure that multiple users can access the same information and work collaboratively from different locations. It is also preferable to, wherever possible, utilise commonly available platforms.

Each of these four enablers is considered in isolation in the subsequent sub-sections of this chapter. They are described and the work and investigations and conclusions are detailed.

6.2 Proposal for a Communication Structure

In order for the effectiveness of CAMARA to be maximised, it is necessary to consider the issues of communications and to establish a ‘communication architecture’ that will:

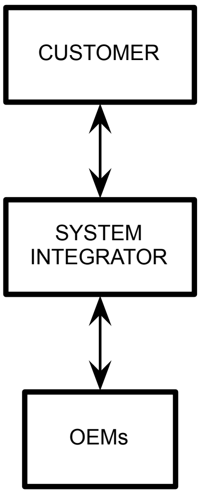
- Represent all of the relevant stakeholders through a new stakeholder model,
- Elicit the necessary requirements information from the relevant stakeholders,
- Link these requirements to the relevant capabilities,
- Outline the various data and information libraries,

6.2.1 Definition of a New Stakeholder Model

In order for CAMARA to be successful, it must address the key requirements of all of the stakeholders involved in the system reconfiguration. The traditional view on the stakeholders is that there are three:

1. The *Customer*. The purchaser and operator of the assembly system.
2. The *System Integrator*. The designer and supplier of the complete system.
3. The *Original Equipment Manufacturers* (OEMs). The suppliers of the equipment modules that are brought together by the System Integrator.

The traditional view represents a relatively simple group relationship between the stakeholders (reference Figure 6-2) and is generally representative of manufacturing. However, due to the extensive use of outsourcing and the extending supply lines, the *Customer* may in fact consist of several different and separate companies or divisions. Furthermore, the concept extends beyond the System Integrator as well, who may employ other System Integrators to provide a sub-assembly of equipment modules, as well as directly procuring some equipment modules. This situation, and the resulting complex group relationship, is represented by Figure 6-3.



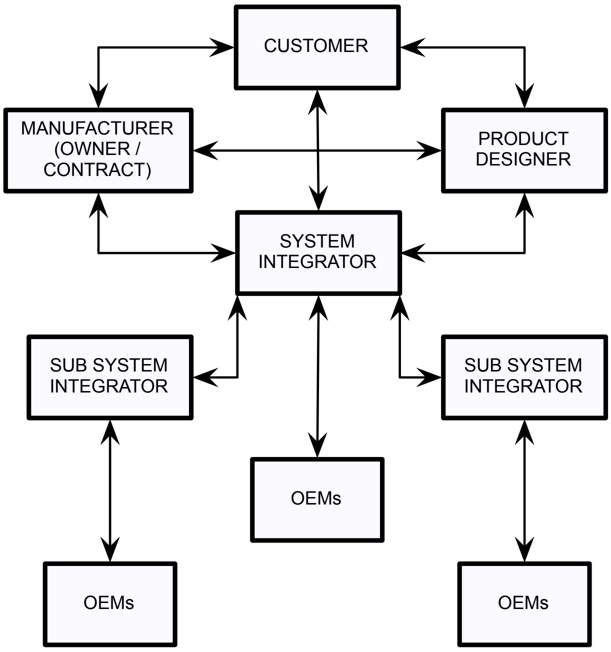


Figure 6-2: Stakeholder links in traditional view

Figure 6-3: Stakeholder links in complex cases

This new and more complex relationship diagram is representative of a number of separate stakeholders in the system reconfiguration process:

The Consumer is the end purchaser and user of the product. This may be a person or company or the general public. This stakeholder is left out of the traditional view because they are not directly involved in the manufacturing process. They are defined here for clarity but do not have a specific part in the model.

The Customer is the person or company requiring the manufacture of the products. The primary concern of this stakeholder is the finances. It is increasingly the case that the final decision on manufacturing capabilities is governed by finances.

The Product Designer is the person or company who produces the product design. This could be a person within the *Customer* organisation, a division within but separate from the *Customer* or a different company contracted to perform the design work.

The Manufacturer is the person or company who own and operate the manufacturing system which produces (or will produce) the product(s). They will almost certainly be selling the products on (rather than using elsewhere in the organisation) and are therefore subject to the marketplace. The production will be for themselves and not a contracted manufacture. The *Manufacturer* can also be the *Product Designer* and/or the *Customer*. **The Contract Manufacturer** is the person or company who own and operate the manufacturing system which produces (or will produce) the product(s). The production will be contracted manufacture; i.e. contracted to produce a certain number of products, of a certain condition, to be delivered at a certain point in time for a fixed sum. This role differs from the *Manufacturer* and cannot also be the *Product Designer* or the *Customer*. The generic term for the manufacturer, used when the exact nature is unknown or irrelevant, is **Manufacturer**.

The System Integrator is the person or company responsible for designing, building and installing the system and bringing it to an operable state. (The system is to be operated by the *Manufacturer*). The *System Integrator* will typically be brought in to install a system; they will be brought back to perform reconfigurations either by prior agreement or on an ad-hoc basis.

The Sub-System Integrator is the person or company commissioned to provide a certain functionality to the system; this will involve integrating a number of equipment modules which are supplied to the *System Integrator*. The *System Integrator* will view this as a single module for planning purposes.

The Original Equipment Manufacturer (OEM) is the person or company who builds and delivers individual equipment modules. These are specified and procured by the *System Integrator*. They have no direct involvement in the system unless specialist consultation is needed or if there is an issue with a particular module.

It can be noted that the original three stakeholders (from the traditional model) are retained. In the case of the Customer, the role has become more focussed. Furthermore, not all stakeholders will be involved in all cases. In particular, the Consumer is rarely directly involved.

The increased number of stakeholders does not only increase the complexity of the group relationships: it also has a dramatic impact on the complexity of the assembly system project. Figure 6-4 shows a simplified view of the assembly system project for the three traditional stakeholders. The Customer provides all of the requirements to the System Integrator, who then develops the system design and the equipment requirements. The System Integrator submits the proposed design to the Customer for approval. If the design is not approved the alterations are made until the design is approved, whereupon the System Integrator sends the equipment requirements to various OEMs, who provide the necessary equipment back to the System Integrator. The System Integrator integrates the equipment in-line with the approved design to produce the complete assembly system, which is then approved (signed off) by the customer (assuming the system is fully functional) who accepts delivery and the project is completed.

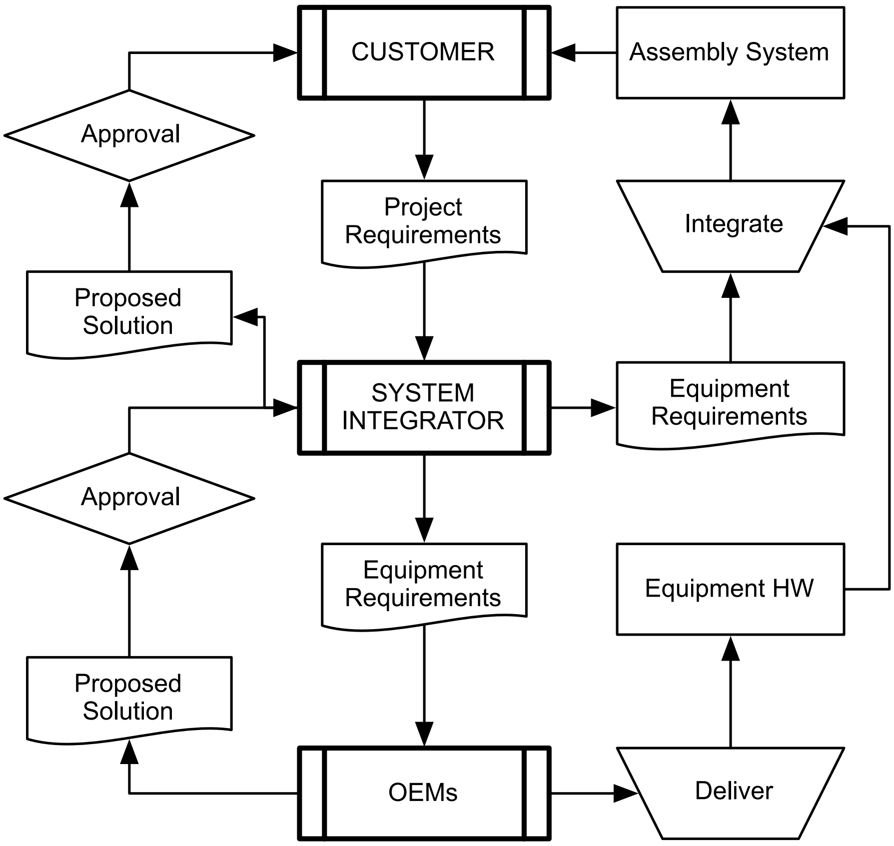


Figure 6-4: Simplified assembly project view for traditional stakeholders

With the increased number of stakeholders and added group complexity, the assembly system project becomes substantially more complex; a simplified view is shown in Figure 6-5. The necessary requirements are given to the System Integrator by the relevant stakeholders: the Customer provides the project requirements, the Product Designer provides the Product requirements and the Manufacturer provides the process requirements. The System Integrator then develops the system design, which is submitted to the Customer for approval. If the design is not approved, the alterations are made until the design is approved. The System Integrator sends the equipment requirements to various OEMs as well as sending the sub-system requirements to various Sub-System Integrators. The necessary equipment modules and sub-systems are delivered back to the System Integrator by the relevant stakeholders. The System Integrator integrates the equipment and sub-systems in-line with the approved design to produce the complete assembly system, which is then approved (signed off) by the Customer and/or Manufacturer (assuming the system is fully functional) who accepts delivery and the project is completed.

6.2.1.1 Implications of the Stakeholder Model

The Stakeholder model summarises the complex relationships between those involved in the specification, design and delivery of an assembly system. The recognition of these Stakeholders and their roles impacts the structure of CAMARA, in particular with respect to the software tool.

There are two main differences between the traditional relationship model and the new complex model. The first difference is that, conventionally, the System Integrator receives the requirements from three different parties: the Customer, Manufacturer and Product Designer. In certain situations, these may be very different and even contradictory. It is important for the purposes of the CAMARA Tool and for potential collaborative development, that these requirements be defined, at least by group and then the necessary communications be managed by an appropriate application.

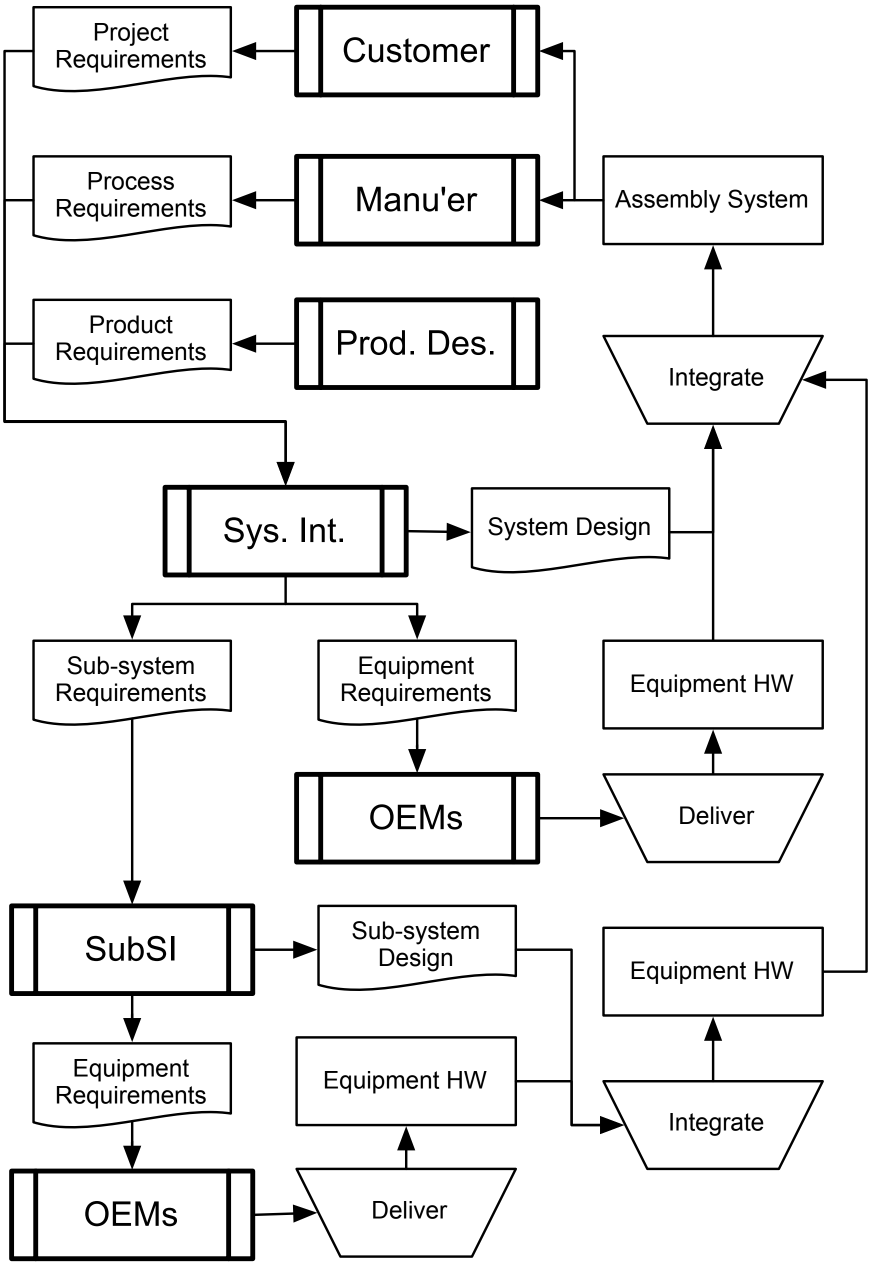


Figure 6-5: Simplified assembly project view for the expanded stakeholders

The other major difference is that the System Integrator not only procures equipment from OEMs but may also outsource sections of the system to other, generally highly specialised, Sub-System Integrators. The selection of equipment by the System Integrator to satisfy the needs of the project in question is an important aspect of the Reconfiguration Methodology and has particular impact on the System Configuration Lifecycle.

In this six-stakeholder model there are noticeably more lines of communication and, although there is no major increase in the volume of data, it becomes even more important to management the movement, use and, perhaps most crucially, updating of this data. This is addressed by the creation and implementation of Reconfiguration Scenarios.

6.2.2 Proposal for Structured Requirements Elicitation

There are two main classes of requirements within this research: the *approach requirements* and the *assembly system requirements*. The *approach requirements*, i.e. what it is that CAMARA must be able to deliver or do, are detailed in Chapter 3. The *Assembly System Requirements*, i.e. what it is that the proposed assembly system solution must be able to deliver or do, are documented in this chapter.

The process of acquiring the information and details relating to the requirements for the particular assembly system project is termed the *Requirements Elicitation*. The conventional means or performing this is through formalised, but unstructured communication. Further to this, the request for information goes to the Customer as represented in the conventional Stakeholder Model (reference Section 6.2.1). One of the biggest challenges associated with Requirements Elicitation concerns the issue of ensuring the right information is sought from the most appropriate source. This becomes even more of a challenge when considering that, in the case of the approach described in this thesis, the information is required by the system integrator before it has been fully defined by the customer. Thus CAMARA proposes the application of a structured *Requirements Elicitation* process based upon the complex stakeholder model.

It can be hypothesised that working with limited information is more likely to produce a solution that is representative of what is required than by inventing requirements at an early stage. Hence the concept of *Reconfiguration Scenarios* is created. By defining the known information in the relevant *Requirement Types*, extrapolations can be made regarding the overall impact on the configuration optimisation, module selection, line-balancing and any other controlled variables within the system. These *Reconfiguration Scenarios* are detailed further in Section 5.2.

The structure in the elicitation process is imparted by the implementation of the software application of CAMARA, which is descried in detail in Section 6.4. The major challenge within this aspect of the work is ensuring that the information is acquired from the most appropriate source at the right stage in the project. The software application makes use of multiple user accounts to ensure that the correct user (and thus stakeholder) defines the correct information. Further to this, ensuring the correct stakeholder is questioned is dependant upon the allocation of requirements to each stakeholder role. In order to do this; the requirements themselves must be divided into appropriate groups.

The *Assembly System Requirements* are, within the context of this work, the list of factors and points that the delivered system configuration must offer and/or enable. This will cover a broad range of topics, primarily related to the product that the system must manufacture.

With respect to the complex stakeholder model described in Section 6.2.1, the Assembly System Requirements are derived from the three stakeholder roles representing the traditional customer; Product Designer, Manufacturer and Customer. These three stakeholder roles each have a different understanding of, and priorities for, the assembly project being specified. By considering these, the requirements can be divided appropriately and each stakeholder role can contribute their expertise within the collaborative environment.

- *Product Designer* delivers the *Product Requirements*. The Product Designer is responsible for designing the product to be produced. Therefore they are best placed to provide the key technical information regarding the product(s) and the constituent components.
- *Manufacturer* delivers the *Process Requirements*. The Manufacturer is responsible for the existing system and the surrounding environment (i.e. the factory etc.) and so is best placed to provide the

necessary information concerning the existing equipment, module availability and the inclusion or prohibition of certain modules, processes or equipment.

- *Customer* delivers the *Project Requirements*. The Customer is responsible for the overall project under which the reconfiguration is to be performed and so is best placed to provide information concerning the overall and non-technical factors. Furthermore, as the Customer is responsible for the budget and project planning; they should control the priorities of the project.

6.2.2.1 Definition of the Product Requirements

The *Product Requirements* are the factors that are directly affected or controlled by the product design and the component parts. As the method is largely product-centred, this area covers most of the technical requirements. The *Product Requirements* can be divided into three main categories*;* *Component Quantitative Data*, *Component Qualitative Data* and *Component Liaisons*.

- *Component Quantitative Data* includes the information that can be attributed to a single numerical value. This is dominated by the information conventionally communicated through engineering drawings, such as geometries, dimensions and tolerances.
- Although typically defined through a single value, within the context of this thesis, linguistic denominators may define these points in order to facilitate the consistent application of the Capability Taxonomy.
- *Component Qualitative Data* includes information that is more subjective in nature. These factors are usually not expressed as a single numerical value, though they may be the accumulation or result of several values or a single linguistic value. This includes factors such as material, rigidity and strength all of which are described linguistically. It also includes points such as the method of delivery and aesthetics.

- *Component Liaisons* refers to the specific relationships between the components. Relationships exist between all of the components within a product (though they may be set to equal zero) and must be identified and defined. In addition, the sequence in which these liaisons are realised is to be defined. This is particularly important in defining the assembly sequence.

Any of the requirement categories listed above can be taken to extreme lengths in the definition process. The volume of information contained within an engineering drawing is vast and it is not sensible to aim to transcribe all of this into any system or methodology manually. Thus, in lieu of fully automated CAD data retrieval and information processing, it is necessary to focus only on the pertinent and valuable information at the relevant stage of design and planning. For example, the dimensions and geometries of a hole in a component will potentially be very useful when the fixture for that component is being designed and machined, however during the overall system planning they are unnecessary details. Thus, the requirements outlined above are condensed to the specific points that affect the planning and specification stages of the system design. These points are specifically linked to the particular taxonomy used.

The information that is pertinent to the system configuration specification is that which impacts the selection of process and module types and thus is linked intrinsically to the Capability Taxonomy. Thus it can be concluded that the Product Designer is responsible for providing the information needed for the definition of the Product Derived Capabilities (Section 4.3.1.2).

6.2.2.2 Definition of the Process Requirements

The process requirements are the factors that either affect or are affected by the assembly system or its environment. These can be grouped into three categories: *Available Equipment*, *Environmental* and *Module Preferences*.

- *Available Equipment* consists of the full listing of the equipment modules available. These fall into two types: Integrated and Zero-Cost as detailed in Section 4.3.1.1; the primary difference between them being that Integrated modules have already been integrated into the system whilst Zero-Cost modules are available at other locations.

- *Environmental* requirements are the factors external to the system itself that have an impact on it. This includes conditions such as temperature, humidity and cleanliness, which may affect the processes or modules selected. It also includes the integration of the configuration within an existing line[8].
- *Module Preferences* covers any particular requirements or limitations with respect to the processes or equipment implemented in the system. Particular Manufacturers may wish to only use, or to exclude, certain specific processes and/or equipment makes. This would most likely be due to experience, familiarity and availability of support and spare parts.

Within the context of this thesis, the primary information within this area is that of the available equipment as this affects the selection and optimisation of the configuration(s). The other information is used within the Equipment Validation phase that, whilst important, can only be efficiently conducted with a substantial Equipment Library in place. It can be concluded that the Manufacturer is responsible for the provision of the information necessary to define the Equipment Derived Capabilities and the Equipment Selection.

6.2.2.3 Definition of the Project Requirements

The project requirements are the factors which are controlled from a business perspective. These do not impact the immediate technical challenge, but rather focus the selection and optimisation processes. This includes:

- Product production sequence (if known/defined)
- System performance criteria (e.g. throughput target)
- Allowable downtime for reconfiguration
- Budget
- Risk acceptance/aversion

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[8] In many larger factories, the assembly lines are divided into sections that may be upgraded at separate times from one another. This is particularly the case when the final product consists of a number of complex sub-assemblies.

Essentially, these requirements define and ensure that the system configuration provides and adheres to the business case. Thus it can be concluded that the Customer must provide the information needed to select and define the Reconfiguration Scenario for the project.

6.2.2.4 Definition of the Cost Requirement

The *Cost Requirement* is the budgetary limit the customer has in the procurement of a new system or configuration. Generally, cost must be considered as the combination of two elements: the initial and the running costs. The initial costs comprise of the direct equipment costs in procuring the modules and the cost of integration (design, installation, programming etc.). The running costs are all of the costs associated with the production of the products, excluding the material and component part costs, typically including the power consumption (and any other similar overheads), equipment maintenance and any personnel costs. In the majority of cases, by far the largest portion of running costs comprises the cost of employees.

In the case of this thesis, where RASs are implemented to produce comparatively small batches of high-value products, it is proposed and assumed that the initial cost of new equipment modules is substantially greater than the running costs. This is the result of the use of fully automated assembly solutions – thereby minimising the number, and costs, of workers. Any workers are assumed to be performing secondary supporting roles that would exist regardless of exact system configuration. Equally, the power consumption differences between equipment are assumed to be several orders of magnitude lower than the procurement costs. It is therefore proposed that running costs be a fixed value, set by the system integrator to give the customer an accurate cost projection, but that for the purposes of comparison activities, a constant value can be provided for the running costs of the different capability classes.

A similar principle can be applied to the secondary element of the initial cost: the cost of integration. One of the primary benefits of the RAS paradigm is that the integration and reconfiguration of modules is defined by a prescribed and predetermined series of actions. Thus for each system architecture it can be assumed that a set amount of time and effort can be ascribed to each module class (following the *six capability classes* from the taxonomy). The precise calculation and value of this should be the role of the system integrator; the ability to integrate equipment is one of the key differentials between competitor companies, as indeed may be the specific system architecture used. Therefore, attempting to standardise or generalise such numbers would be counter-productive.

The consideration of the points described above leads to a statement of definition of the cost requirement considered in this work:

$$\boldsymbol{\kappa_R = \Sigma\ (\kappa_{PE}) + \Sigma(\kappa_{IE}) + \Sigma(\kappa_{OE})}$$

Where:

κ_R = the Required Cost

κ_{PE} = the procurement costs of the equipment

κ_{IE} = the integration costs of the equipment

κ_{OE} = the operational costs of the equipment

The determination and projection of this calculation is described in further detail in Chapter 6.

6.2.2.5 Definition of the Performance Requirement

The *Performance Requirement* is the generic description for one key performance indicator (KPI) chosen by the customer. There are a number of standard KPIs in assembly automation, the most commonly used and defined being:

- *Cycle Time* is the frequency with which a completed part is delivered by the system. It is not representative of the actual time taken to assembly the product. It is expressed as a unit of time (e.g. 3.50 seconds).
- *Product Failure Rate* is the number of parts in a set that fail to meet specified quality criteria. In high production volume systems, it is often referred to as a 'sigma' (six-sigma, five-sigma), which is a function of standard deviation. It can in all cases be expressed as a percentage (e.g. 0.01%).

- *Production Output* is essentially a combination of the two previous KPIs. It is the number of acceptable products delivered in a set unit of time. It is therefore expressed as a number per unit time (e.g. '100,000 units per year' or '60 units per hour')

It is proposed that, in the case of the batch Reconfiguration Scenario that forms the basis for this work, the most important KPI is *Production Output*. This is because it is assumed that the most important purpose of the system is to deliver the batch as soon as possible. *Production Output* represents the successful products produced as a function of the speed and quality of the system. The implementation of specific quality methods within a short production run environment is unlikely to offer any net gains in productivity and what is most important is the availability of acceptable parts. Therefore, this thesis focuses primarily of performance as represented by the *Production Output* KPI variable, which can be expressed as:

$$\mathbf{\Pi_O = [n_{GP} - n_{BP}] / T_P}$$

Where:

Π_O = production output

n_{GP} = number of 'good parts' produced

n_{BP} = number of 'bad parts' produced

T_P = production time required for both good and bad parts

The KPIs described in this section focus on the delivery of the products, which is a highly important aspect of any manufacturing system. However, whilst these are descriptive of the overall capability of the system, they are directly related to the production once it is operational. A critical feature of RAS is the ability and need to become operational quickly, thus the third requirement is included.

6.2.2.6 Definition of the Time Requirement

The *Time Requirement* covers the issues associated with the time during which the system is not operational. It is separate for the time aspects of the *Performance Requirement* and does not represent the actual production timescales. The *Time Requirement* is conventionally dominated by the lead-time: the time taken from completion of the order to the delivery of the operational system. Lead-time is the time taken for the system to be operationally available and is itself generally governed by the lead-times associated with the individual and specific equipment modules.

However, within RAS, and particularly in the case of multiple system configurations for multiple products, the more important issue is that of the *Reconfiguration Time*.

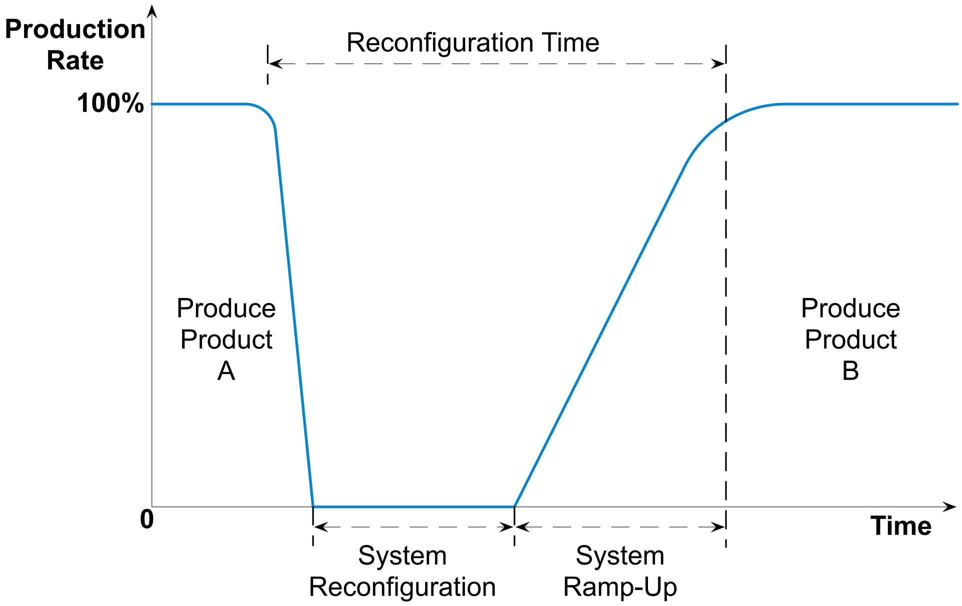

Figure 6-6: Representation of the *Reconfiguration Time*

Reconfiguration Time is the time taken to realise a reconfiguration of the system. Figure 6-6 provides a representation of Reconfiguration Time on a graph of time against production rate, which shows that it is composed of the time taken to reconfigure the system (when production rate is equal to zero) and the time taken to ramp-up production rate from zero to one-hundred percent. Thus, Reconfiguration Time can be defined as *the time taken to reconfigure a fully operational system producing one product to another fully operational configuration for a different product.* This definition is subjective to the degree of reconfiguration; certainly it is presumed that the framework and architecture will not be changed. However, the reconfiguration may require no more than changing of tooling (fixtures, grippers etc.) or may require that every existing equipment module be replaced.

This definition places, in most cases, the emphasis on the time taken to make the changes to the architecture rather than concerns over the time taken to procure the modules. Given that the cost of integration for a RAS can be defined as being a constant, and the majority of the cost associated with the integration of a new module is the time taken, the physical aspects of the reconfiguration can be found as a function of the number and types of module being changed/added/removed.

The emphasis on the time taken to make the changes applies when the reconfiguration is being considered during a planning phase that will not affect current productivity. This is the case when changes to products are being forecast and planned based on expected changes. In the case of unpredicted events affecting production, such as equipment failure or sudden product changes (caused by, for example, order cancellation or unavailable components), CAMARA may still be employed in order to define the most efficient means to regain operability. In this case, the lead-time associated with any new equipment will have an impact and be an important part of the planning process. The definition above supports this by focussing on maintaining the system at full production capacity.

The most variable aspect of the definition is with respect to the ramp-up time. The ramp-up phase of reconfiguration involves first switching the system on and testing it, then identifying and resolving any issues that are preventing the system from reaching full production capacity. In conventional systems, this can be a particularly complex phase that can result in a significant proportion of parts failing to meet the quality standard required. This typically requires a significant amount of re-working of the products.

Furthermore, reworking of products during standard production is an issue. In cases where the cause of failure can be identified as directly attributable to the assembly process, RASs have the potential to be more easily adapted to prevent the error from re-occuring. Whilst RASs can be implemented to support and/or reduce rework in all forms, these considerations are outside the scope of this work.

Whilst the RAS paradigm simplifies and removes some of the variables (primarily through the implementation of the standardised architecture, system layout and interfaces) it is likely that there will remain a number of unknown and unpredictable variations that will affect the ramp-up time for each configuration. Therefore it is proposed that the system integrator will provide an estimation of the reconfiguration time based upon the specification produced at the end of the *Reconfiguration Methodology*. This will provide greater accuracy, however it does not support the 'quick-view' target of this thesis. It is therefore proposed that one element of the calculation of the *Reconfiguration Time* be a prediction of the ramp-up effort based upon a weighting of the module classes.

Reconfiguration Time can therefore be calculated as:

$$\mathbf{T_R = \Sigma T_{ME} + T_{RU} + (T_{EL} - T_{OS})}$$

Where:

T_R = Reconfiguration Time

T_{ME} = Module exchange time

T_{RU} = ramp-up time

T_{EL} = equipment lead-time

T_{OS} = operational system time (i.e. the time during which the old configuration is fully operation)

In the majority of cases (where the reconfiguration is being planned ahead and so the modules will be in place):

$$\mathbf{(T_{EL} - T_{OS}) = 0}$$

6.2.3 Links Between the Requirements and the Relevant Capabilities

Each of the types of requirements described in Section 6.2.2 has links to one or more of the functions of the Capability Model and/or Reconfiguration Methodology, described in Chapters 4 and 5 respectively. It is necessary to understand and define the influence and connections of the requirements, particularly for full traceability of data, but also to gain greater clarity of the exact information needed. This is considered, in this case, specifically with respect to the Microassembly Capability Taxonomy.

The **Product Requirements** are the primary source of information for the definition of the Required Capabilities. After the Required Capabilities have been identified, they must be defined. This can be done on an ‘ad-hoc’ basis – whereby each Capability is defined through the Taxonomy by the user who has a detailed knowledge and understanding of the relevant parts.

The alternative, which is applicable when the user is unfamiliar with the parts or when there is a large volume of data or when the same components are used repeatedly, is to utilise the definition of the Product Requirements to assist in the definition process. These links are established through the Capability Class Structure, as outlined in Figure 6-7. It should be noted that in order for the complete definition of the Required Capabilities, it is necessary to also link to information regarding the existing system architecture. Furthermore, the specification of the Work and Measure classes are expected to require information on the raw materials and the required quality respectively.

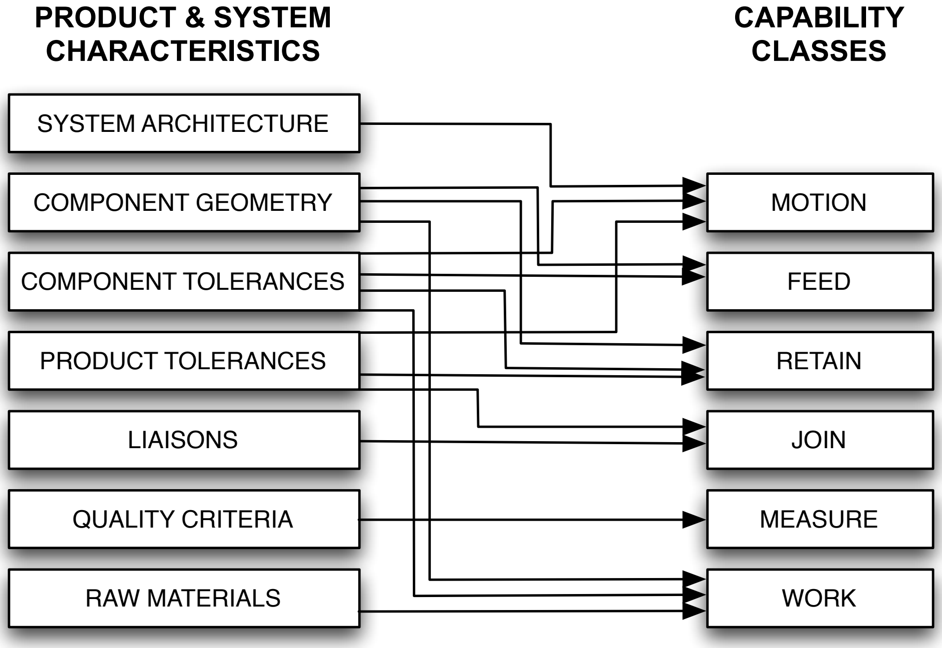

Figure 6-7: Links between Product and System Characteristics and the Capability Classes

The other two sets have a far less complex set of links. The **Process Requirements** are important in two areas: the definition of the Existing Capabilities (directly from the Available Equipment List) and the final selection of equipment models described in Section 5.3.5.3, which may be affected by any specific notes on modules to exclude or include. The **Project**

Requirements are directly linked to the overall Requirements and Priorities in the tool described in Section 5.1.6.

6.2.4 Requirements Evaluation to Ensure Feasibility of a Solution

The primary requirements for reconfiguration can be divided into three key categories: *Cost (κ)*, *Performance (P)* and *Time (T)*. Each of these can represent a multitude of different measurable and quantifiable factors, but grouping them enables their early consideration. This can be performed before exact details are known or defined and, in-line with one of the key aims of this thesis, provide a 'quick-view' of the possibilities and implications of decisions.

These requirements are defined within four key areas, as defined in Section 5.1.4, Product, Equipment, Environment and Priorities. It is not suggested that this is an exhaustive list of all possible factors or priorities. However, this does form the basis for the initial investigation.

6.2.5 Proposal for a Requirement-Priority Tool

This tool provides a plot area representing the requirements. It includes boundaries within the plot area to represent the nature of the likely assembly system/configuration solution. When the requirements for each application are plotted and the solution nature identified, the priorities can be used to, where necessary, recommend the optimum approach for altering the requirements as well as providing the basis for the reconfiguration strategy. The process of implementing the tool is for the user to calculate or determine values for each of the requirements and for these to be plotted. The location of the plot will enable certain conclusions to be immediately drawn. Then the priorities are considered: the user must rank each of the priorities depending upon the particular circumstances and needs of the application. These will then be considered during the determination of whether any requirements changes must be made to ensure a viable solution can be found and during the selection of the appropriate reconfiguration strategy (detailed in Section 5.3).

The following sub-sections describe the two variants of the tool: the 2-Dimensional and the 3-Dimensional. The number of dimensions refers to the axes on the graph, which represent the requirements considered. Conventional system specification does not focus on the *Time requirement* as a separate functional requirement; instead it is a consequence of the exact equipment modules selected[9]. Therefore, the 2-Dimensional tool is suited to such applications, as well as to cases where the reconfiguration time is several orders of magnitude lower than the expected production timeframe. Furthermore, developing a tool in two axes and then expanding into the third is a prudent developmental approach and one that is adopted here.

6.2.5.1 The 2-Dimensional Tool

The conventional trade-off of the requirements considered during the design and specification of an assembly system is between *cost* and *performance*. Figure 6-8 shows a representation of the priority space that is, in the conventional case, two-dimensional. Cost, with respect to an assembly system, is a variable dependant upon complexity. From a purely scientific perspective, the tool should represent complexity in place of cost; however, the discussions described in Section 3.5.1 suggested that customers would prefer to consider the cost function, not least as it is both easier to calculate and determine retrospectively and it is less subjective.

Generally; an increase in cost results in an increase in performance. Time is not specifically considered in the first instance. This is because, whilst lead-times are important, they are the result of the availability of specific models of equipment rather than types or the overall solution. Also, the additional complexity of the integration of one type of module over another is relatively small in comparison to the effort and time taken in the design, integration and testing of the complete system.

Another important point to note is that Figure 6-8 does not show a linear relationship between cost and performance. Generally speaking, the relationship is governed by ‘diminishing gains’. Starting from the base of zero-zero, increasing expenditure rapidly increases the performance. However, as cost increases, the quantifiable performance gains are smaller for each linear step in cost. Eventually, this graph will flatten out and further cost increases will yield no benefit in performance. The graph can be used to plot whether the

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[9] Generally, this will be considered during more detailed system specification: the available time will be finite and so this will govern the equipment selected. This may result in the optimal solution being rejected in favour of one that is available quicker.

desired performance and cost can be met by a single system. Figure 6-9 shows three example plots on the 2-D trade-off graph: A, B and C. Plot A is above the trend-line, which shows that the required performance cannot be achieved at the cost required. Plot B is on the trend-line, which shows that the cost and performance are achievable simultaneously. Plot C is below the trend-line, which indicates that the desired performance can be met at a lower cost than is acceptable. These figures have been determined based upon the discussions described in Section 3.5.

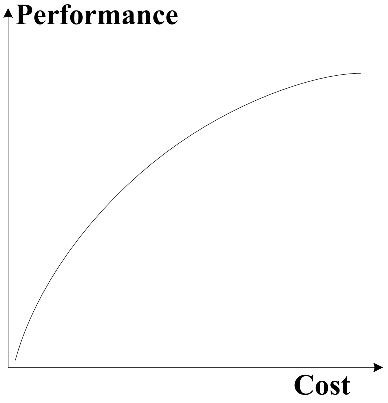

Figure 6-8: The conventional trade-off for assembly system specification

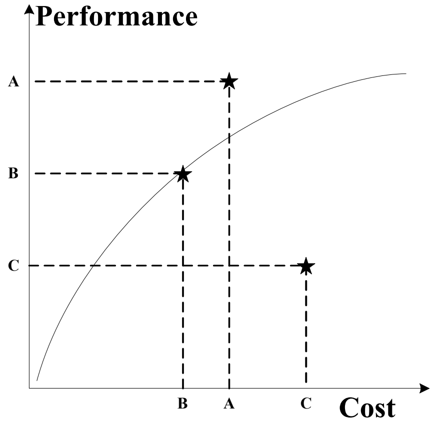

Figure 6-9: Example plots on the 2-D trade-off graph

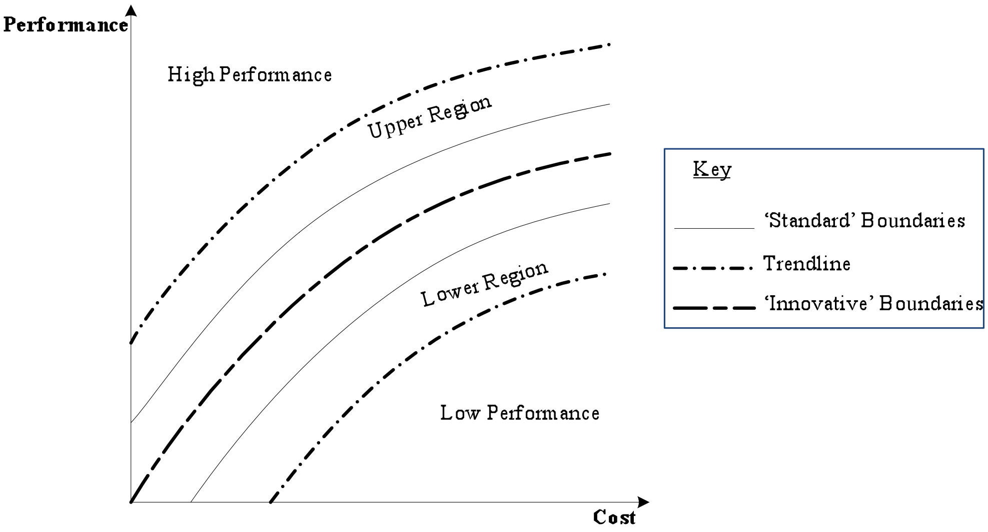

Figure 6-10: The hypothesised 2-D Priority Space Graph

It is hypothesised that Figure 6-8 can be expanded to be more representative of the variations in equipment types and innovative solutions. The expanded trade-off proposed is the *Priority Space Graph* and is depicted in Figure 6-10, which shows a more complex plot area[10]. The proposed concept is that the traditional trade-off (which is typically not plotted on a graph, but rather calculated manually based on separate projections of the cost and performance of the solution) can be expanded into a useful tool. The user forms this tool, the *Priority Space Graph*, from the collection of relevant data. The proposed approach is that each CAMARA user or system integrator record their own data and apply it to the standardised graph to determine the exact location of the boundaries (described below). This is proposed because the differences and nuances between individual integrators, designers, system architectures and production domains will have a substantial impact on the location and shape of each boundary. The description below is for the generic approach, which should apply regardless of the specifities of the application or data.

The plot area comprises of the *central trend-line*, two *standard boundaries* and two *innovative boundaries*. The *central trend-line* represents the average, or middle, points on the plot for any assembly system solutions. The *standard boundaries* represent the spread of values for conventional assembly system solutions, i.e. those solutions that employ off-the-shelf equipment in 'traditional' formats and layouts. The innovative boundaries represent the extremes of potential solutions: those which employ non-conventional equipment or techniques. These boundaries aim to reflect and represent the constant technological advances and evolution within assembly equipment, particularly in the micro domain.

The use of the 2-D Priority Space is not simply to assess whether or not two priorities can be met, but the implications of doing so. To this end, the location of an individual plot enables conclusions to be drawn: this is made feasible by the inclusion of the additional boundaries around the *central trend-line*. These

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[10] All of these graphs are shown in generic forms. Their precise details and implementation require detailed study of legacy systems and solutions and the inputting of relevant and accurate data. Such efforts are supported by the CAMARA principles, which propose substantial use of data logging for learning, quality assurance and to accelerate the timescales of the process owith increasing experience.

conclusions are based upon the location of the individual plot within the Priority Space:

- The *central standard region* of the graph between the two standard boundaries represents the area of conventional assembly system solutions. Generally, a plot located within this region will be achievable and comparatively low-risk. Specification work could continue without further priority consideration.
- The *upper innovative region* of the graph between the upper standard and innovative boundaries represents the area where the required performance is potentially available at the required cost, but the solution is likely to be innovative and non-standard and result in substantially higher risks of failure and/or delays. Specification could continue, but with caution. Reconsideration of priorities is suggested.
- The *high performance region* of the graph above the upper innovative boundary represents the area where the available budget cannot delivery a suitable performance. Specification cannot continue and the priorities must be adjusted, either an increase in budget or a reduction in required performance.
- The *lower innovtive region* of the graph between the lower standard and innovative boundaries represents the area where the required performance is comfortably achievable within budget. Specification could continue as a solution can be found but it is recommended to re-evaluate the priorities to either reduce the budget or increase performance. However, there will also be the option of utilising non-standard and innovative solutions that may offer additional benefits outside of the scope of the graph.
- The *low performance region* of the graph below the lower innovative boundary represents the area where the required performance can be easily achieved within budget. Specification could continue as the solution will work. However, it is recommended that priorities be reconsidered: a higher performance

is achievable for the cost or the same performance can be achieved with a lower budget. The current priority balance is inefficient.

Further to this, the priorities of the user will affect the recommended stratagem. The 2-D space represents two requirements; *cost* and *performance*, which are also two of the priorities, but there are two further priorities in *risk* and *efficiency*. The ranking and weighting of these four priorities has a major influence on whether the existing plot location is acceptable and, if not, how and where it can be moved.

The application of these conclusions and guidelines for the 2-D Priority Space Graph will enable the user to understand the nature of the likely results from the specification procedure. Figure 6-11 shows some example plots on the graph. Plot J is located on the *upper standard boundary*, plot K is located in the *upper region*, plot L is in the *lower region*, plot M is on the *central trend-line* and plot N is in the *high performance region*. Each of these plots will be assessed and the suggested next actions described.

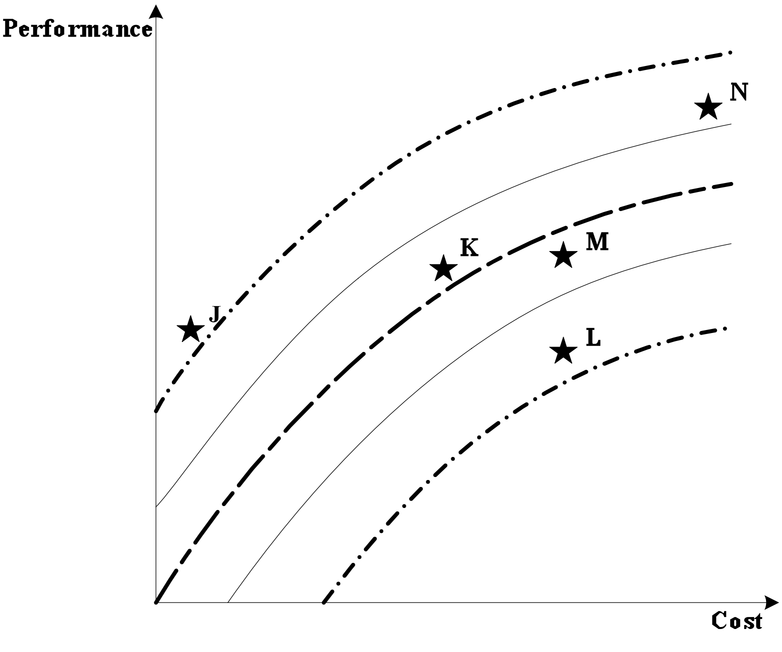


Figure 6-11: Example plots on the 2-D Priority Space Graph

Plot J is located in the *upper region* at a point of the curve with a relatively high gradient. As it is a borderline case, the specification could continue but is likely to rely on an innovative and high-risk solution. The recommendation would be to alter the priority balance to bring the plot closer to the *central* *trend-line*. In this case, due to the gradient of the curve, the same performance could be achieved for a comparatively small increase in budget, therefore the proposal would be for a **small increase in budget**.

Plot K is located on the *upper standard boundary* at a point of the curve with moderate gradient. Due to the plot location, the specification can continue and is likely to produce a workable and suitable result. However, the recommendation would be to **exercise caution during the specification** as the solution might have a degree of innovation and risk associated to it.

Plot L is located in the *lower region* at a point on the curve with moderate gradient. The location of this plot indicates that the required performance and cost are comfortably achievable and so specification can continue. However, the recommendation would be to consider one of two options: either to **maintain the cost level and investigate the benefits of an increase in performance** or to **reduce the allowed budget**, saving money and increasing overall efficiency.

Plot M is located on the *central trend-line*. This indicates that the current priorities are perfectly balanced at their current levels and that the specified system will deliver the performance required in budget. The recommendation is that **no changes are made**.

Plot N is located in the *high performance region* close to the low gradient portion of the curve. This plot location indicates that there is unlikely to be any suitable system solution. As the point is close to the lowest gradient of the curve, even a substantial increase in budget may not enable the realisation of a satisfactory solution, however a relatively small reduction in the required performance will bring the plot into the *central region*. Therefore the recommendation is that the **performance requirement be reduced**.

The main purpose of the 2-D Priority Space is to enable users to plot and see the impact of their priorities and requirements. For example, in the case of plot J above, the initial requirements cannot be met by a conventional system solution. If *cost* is the predominant priority, then the performance requirement will have to be reduced – how far will be dependant on the level of risk aversion. If *risk* is the second priority then the performance requirement will need to be reduced such that the plot falls below the *upper standard boundary*. However, if *risk* is prioritised below *performance*, then the performance requirement should only be dropped such that the plot falls below the *upper innovative boundary*.

The 2-D Priority Space Graph described above is intended for implementation in cases where timeframes are not important and so do not feature as a main requirement. The addition of a third requirement to the graph results in a three-dimensional plot area. This substantially increases the complexity of the analysis and leads to a 3-D Priority Space Graph, which is described in the following section.

6.2.5.2 The 3-Dimensional Tool

The major issue with the 2-Dimensional tool is that it does not consider the *reconfiguration time requirement*. This results in the exclusion of a key consideration within the methodology. The 2-Dimensional tool enables a singular solution to be optimised prior to full specification The 3-Dimensional tool allows for the consideration of the factor most likely to impact the implementation of RAS and the high-value, low volume products: *reconfiguration time*. Further to the considerations made during the 2-D tool, *complexity* was determined to be a possible option for a third dimension; it is a factor impacting upon both cost and reconfiguration time and so cannot replace both, but is also not the preferred means of data presentation due to it's subjectivity and difficulty of calculation.

Figure 6-12 shows the extrapolation of the 2-D graph, assuming there is no relationship between performance/cost and the reconfiguration time. Figure 6-13 shows a displaced curve, which is based upon the more realistic assumption that an increase in Reconfiguration Time (T_R) results in an increase in cost and in Performance (P). Figure 6-14 shows a 2-D graph of T_R vs P. This shows that, as T_R increases, so does performance. The start point is not zero-zero because of the existing performance of the system. The boundaries offer an expanding range of options:

- The increase in time taken to reconfigure opens more opportunities and possibilities for system change and thus the potential for performance gains (Blue Line).
- It is assumed that performance does not decrease after reconfiguration (Green Line)
- However, this may not be the case as the required performance for the new configuration may in fact be lower, or the recnfiguration effort has resulted in a failure (Orange Line). This leads to the conclusion that the existing state of the system has a major bearing on the shape of this graph.

Figure 6-15 shows some of the options where the existing system performance is variable:

- In the case of a high starting P (Blue Line), then the upper boundary slowly angles up towards ‘maximum’. The lower boundary however, quickly drops away towards zero (though the zero line is never reached as the assumption is made that complete loss of performance of the system is not a reconfiguration but either decommissioning or failure).
- For the case of a low starting P (Green Line), the upper boundary quickly increases whilst the lower boundary reaches minimum in a short distance due to the proximity to the zero plane.
- For the case of medium starting P (Red Line), the upper and lower boundaries commence with similar, but opposite, gradients towards maximum and minimum values.

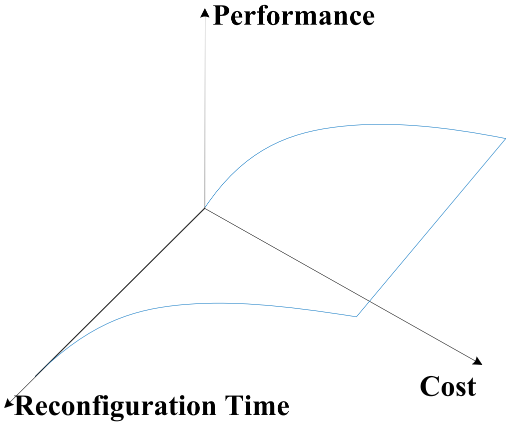


Figure 6-12: Plot of trend on 3-Dimensional graph, assuming no relationship between Reconfiguration Time and the Performance-Cost curve

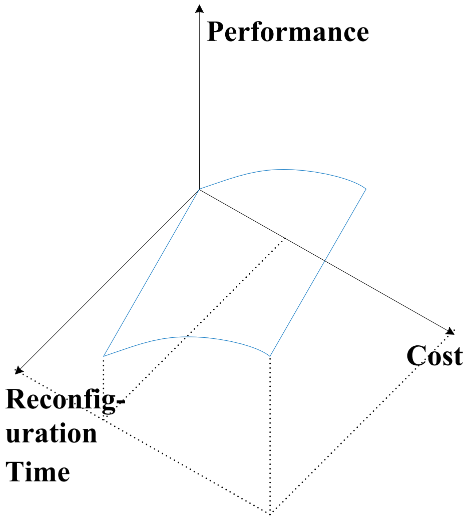


Figure 6-13: Plot of trend on 3-Dimensional graph, assuming an increase in Reconfiguration Time results in a default increase in Performance and Cost

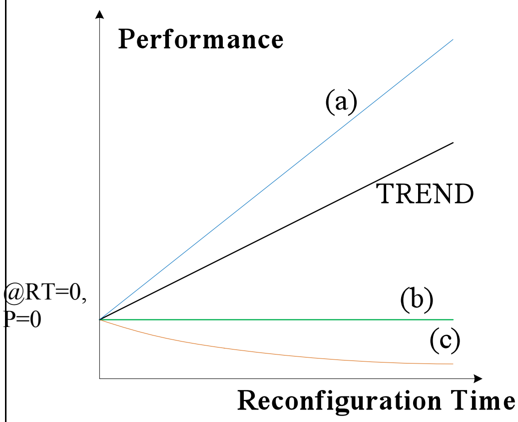


Figure 6-14: Plot of the relationship between Reconfiguration Time (T_R) and Performance (P), with boundary lines

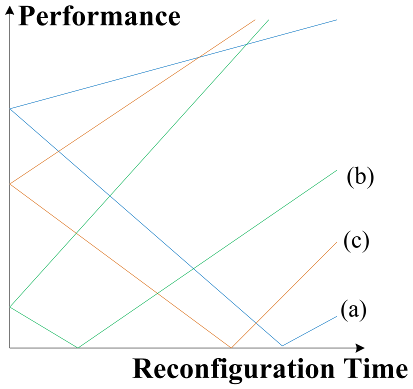


Figure 6-15: Plot of the relationship between T_R and P for three different existing system performance levels

In all three cases described by Figure 6-15, the upper boundaries will begin to flatten as they reach their maximum due to the anticipated experience of the ‘diminishing gains’. Furthermore, as each of the lower boundaries reaches the zero point the curve then redirects upwards. This is because once the minimum performance value has been reached; any additional reconfiguration time (and thus effort) must be expended on increasing the performance. These plots highlight the complexity of the multivariate considerations.

Further to this, Figure 6-16 shows a plot of the relationship between Cost (κ) and T_R. In this case, the relationship is somewhat simpler: an increase in T_R increases the κ. The plot starts at the zero-zero position because no costs are incurred until some reconfiguration is completed. However, whilst the average trend-line can be represented as a linear one, there are large boundaries. This is due to the vast range of possibilities of module exchange. In an RAS, the time to exchange any module is broadly similar, and so the labour costs are constant. However, the initial cost of the equipment can vary enormously, leading to an ever-increasing gap between boundaries as the Reconfiguration Time increases.

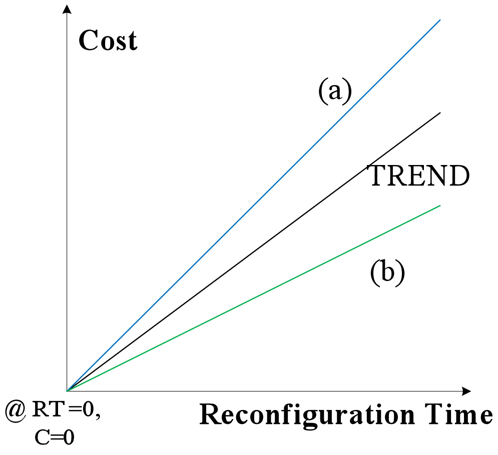


Figure 6-16: Plot of the relationship between Cost and Reconfiguration Time

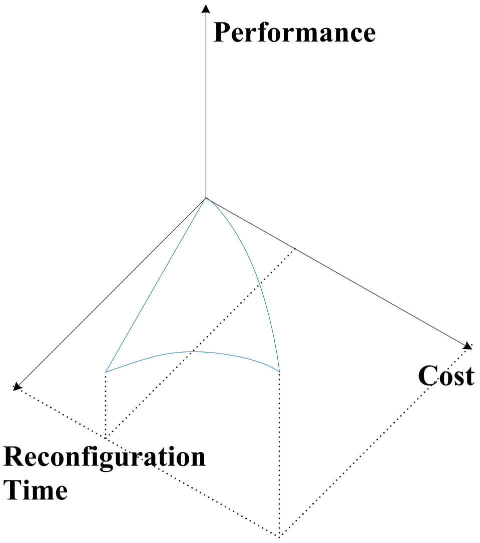


Figure 6-17: Plot of the combined relationships showing the trend-line only

Figure 6-17 shows a funnel shape. This is the result of the assumption that a reduced T_R ultimately reduces the number of possible solutions by restricting the number of module changes. Thus the length of the curve is reduced.

The major problem with the combination of the three requirements into a single plot space is that the interactions and relationships between T_R and κ and between T_R and P are very different. Whilst a single plot area is possible, it is not realistically feasible.

The ultimate conclusion is that inclusion of a third axis increases the complexity of use and the volume of data required to deliver a useful plot area and curves. The proposal is for a modified 2-D approach, whereby the T_R requirement is considered as a major influencer of the reconfiguration strategy.

The consideration of the Reconfiguration Time is to be made by the implementation of a multi-solution projection approach. This approach utilises the Three Capability Lists produced by the Capability Model. The Compatible Capability Set effectively sets the boundary conditions for reconfiguration (where the proposed configurations are bounded by ‘sensible’ limits for the relevant application and situation and not by the extremes of what is possible). This leads to the proposal for consideration of Maximum, Minimum and Mean Configurations, described in Sections 4.3.3.2 and 5.1.7.

6.2.6 Data Libraries

One of the key features and benefits of CAMARA is that of information retention and traceability within a process that is conventionally not particularly suited to either. In order to deliver this, a series of information libraries are needed. These are to be populated with information acquired from external sources, the different stakeholders as well as experiential data.

A key requirement for these libraries is that they are comparatively easily populated, updated, queried and recalled. These libraries are briefly described in the subsequent sub-sections.

6.2.6.1 Equipment Library

In order to both define the *Available Capabilities* and to allocate equipment to new configurations, an *Equipment Library* is required. This consists of a database of equipment modules – the key information being:

- Module make and model. There should be sufficient information to enable the correct module to be procured.
- Text description. Not necessary, but a brief human-centred description to facilitate manual searching of the library (e.g. “Small SCARA robot”).
- Capabilities offered. This subsequently defines all operational functionality.
- Architecture compatibility. This field is specific to the consideration of modular systems: the different modular architectures will require

different interfaces and different spatial constrictions. Thus the compatibility of modules is listed to further accelerate the equipment selection process.

- Cost. The list price of the module.
- Lead-time. The estimated lead time / availability of the module.
- Environment. Any specific environmental requirements, such as the necessary temperature and humidity ranges.

This information is to be tabulated such that matches can be retrieved for any of the key information criteria listed.

6.2.6.2 System / Solution Library

With each iteration conducted through CAMARA, solutions are generated. It is thus proposed that the solutions generated and implemented be stored in a database along with the relevant requirements and any notes on the success of implementation (where relevant). Hence, in future projects, one of the first stages of solution development would be to search previous solutions for one that is comparable utilising Case-based Reasoning. This would form a potential risk mitigation strategy, as the solution found in the database would not be an unknown.

The benefit of storing and searching the generated solutions and the associated requirement for data capacity would need to be weighed against the process of calculating the solution each time. For the purposes of this thesis it is assumed that only implemented solutions are retained within the library.

6.2.6.3 Product and Component Library

One of the major methods for Product Designers to minimise the cost of implementing new products is to, wherever possible, utilise common components. This is often seen in the form of nuts, bolts and screws, but is becoming increasingly used in consumer goods that are designed around a single modular platform, offering numerous variants and upgrades over time. The impact of this is that the same components are often re-used in new products. So it is proposed that a library of components be created and populated such that the effort in the specification of a new product be minimised as far as is possible.

It is proposed that all of the libraries described in the preceding sections consist of different levels of privacy. Some may be made globally searchable such that any CAMARA users can access the information. This is most likely to be the case for equipment and for common components. Others may be retained as private for a particular user or group of users, particularly the solutions used. This is an intrinsic aspect of the collaborative environment and a function of the implementation of user accounts.

6.3 Consideration of Micro Products and Assembly Equipment

One of the key features of the work within the 3D-M project is the simultaneous consideration of the equipment used and the products delivered for the realisation of integrated assembly processes. As highlighted in Section 2.2.1.4, the design and development of Microdevices is often made more complex by the difficulty in applying prototyping technologies and processes to mass-production. Thus it can be proposed that a key enabler in the delivery of microdevices is the consideration of an integrated assembly system and assembly processes. Further to this, the development of communication structures and appropriate software tools are additional points addressed in the course of enabling the CAMARA Tool.

6.3.1 Introduction

The specific consideration of Assembly Equipment is essential in order for an RAS to be implemented, particularly in the micro domain: it is necessary to use the appropriate hardware. Further to this, the products and devices produced by this equipment must also be considered – it is only through the investigation of both Products and Equipment that integrated assembly processes can be realised.

The Assembly Equipment can be divided into two broad categories: the *Framework* and the *Modules*. The *Framework* contains the *Modules*. The Framework is perceived as fixed and does not change during reconfigurations, whilst the Modules are interchangeable and changing them is the focus of the reconfiguration process. Furthermore, the Modules impart their functionality on the product; the Framework supports the Modules in this.

Understanding and evaluating the available Framework supports the Reconfiguration Methodology by clearly identifying the configurations and module layouts that are possible. Assessing the Modules is a fundamental aspect of the Capability Model; without an accurate understanding and definition of the available capabilities, the rest of the approach has no benefit.

Consideration of Microdevices is made within the 3D-M project in the form of three test cases products. These have been conceived, designed and developed within the project in a manner consistent with its aims and objectives. Furthermore, the test cases themselves have enabled these processes and their integration to be refined. The scope of this thesis is not to specifically cover the design of devices (although it is possible that the CAMARA Tool may be used in support of other DFA activities) but it does utilise two of the three 3D-M test cases as the basis for development of innovative assembly processes, presented in Section 7.3.

The 3D-M project specifically considered the issue of the integration of processes within a single platform as well as the development of innovative micro assembly processes. This work is within the context of the three project test cases; two of which are utilised within this research. Furthermore, through the consideration of a set of specific physical items, the CAMARA tool itself can be better evaluated and recommendations made; both for the use of CAMARA and for the wider application of RAS technologies.

6.3.2 Integration Proposal for a Modular Reconfigurable System

Within the 3D-M project, there are three test case products with the aim that innovative processes developed within the project can produce them. There is, however, the risk that the end result will be a number of entirely independent demonstrator processes and products. These, whilst innovative and successful in their own right, will not fully demonstrate the achievements or potential of the project. Thus it is necessary to provide a proposal for the implementation of a single demonstrator platform. Full details of this proposal are provided in Appendix C.

6.3.2.1 Application within CAMARA

The conducted evaluation of modules, described in Appendix C, has shown that the identification of equipment-based capabilities can be successfully performed by the Capability Identification Process (reference Section 4.3.1.1). Furthermore, it has demonstrated that clear and rigorous rules are necessary to prevent the mis-identification of capabilities that would be of detriment to later analysis. The evaluation of the suitability for integration within an RAS is, as hoped, made relatively straight-forwards by the existing processes (as described in Sections 4.3.1.1 and 4.3.2). However, the evaluation of the physical suitability is far more complex and largely reliant upon an expert understanding of both the RAS architecture and of the modules themselves. This highlights the need for the CAMARA Tool to be supported by a suitable RAS architecture, which should include some of the following features:

- Flexible layout of modules and conveying.
- Centralised intelligent control system.
- Development of a single interface, with the potential for automated module exchange.
- Additional features, such as atmospheric and environmental controls, should be included as a matter of course within the implementation of microdevice production.

The approach described is that proposed and undertaken within the 3D-M project and is representative of the challenges faced in the collaborative development and integration of assembly systems. It shows significant synergies with the CAMARA Tool and also highlights the necessity for a collaborative development environment.

6.4 Application of the Approach Within a Software Environment

One of the fundamentals to the realisation of CAMARA, and to RAS in general, is a set of suitable and appropriate software systems. This thesis divides and discusses software within two distinct areas: *System Control* and *System Planning*. *System Control* is outlined in Section 2.2.3. *System Planning* is the process by which the solution/s to a set of manufacturing challenges is/are arrived at. This is characterised as a human-driven iterative process, the structure of which is usually specific to an individual organisation. The main purpose of CAMARA is to provide a standardised structure and approach to this process within the specific area of RAS with multiple configurations, which is to be delivered through the implementation of a software platform.

6.4.1 Software Selection

In order for CAMARA to be efficient and effective, it is necessary for the individual tools, methods and approaches currently existing in a manual state to be integrated within a singular software environment. This is largely due to the volume of data to be manipulated, which makes manual operation of the tools very difficult. The selection of the appropriate tool is based upon a series of factors concerning what the final tool must be able to do:

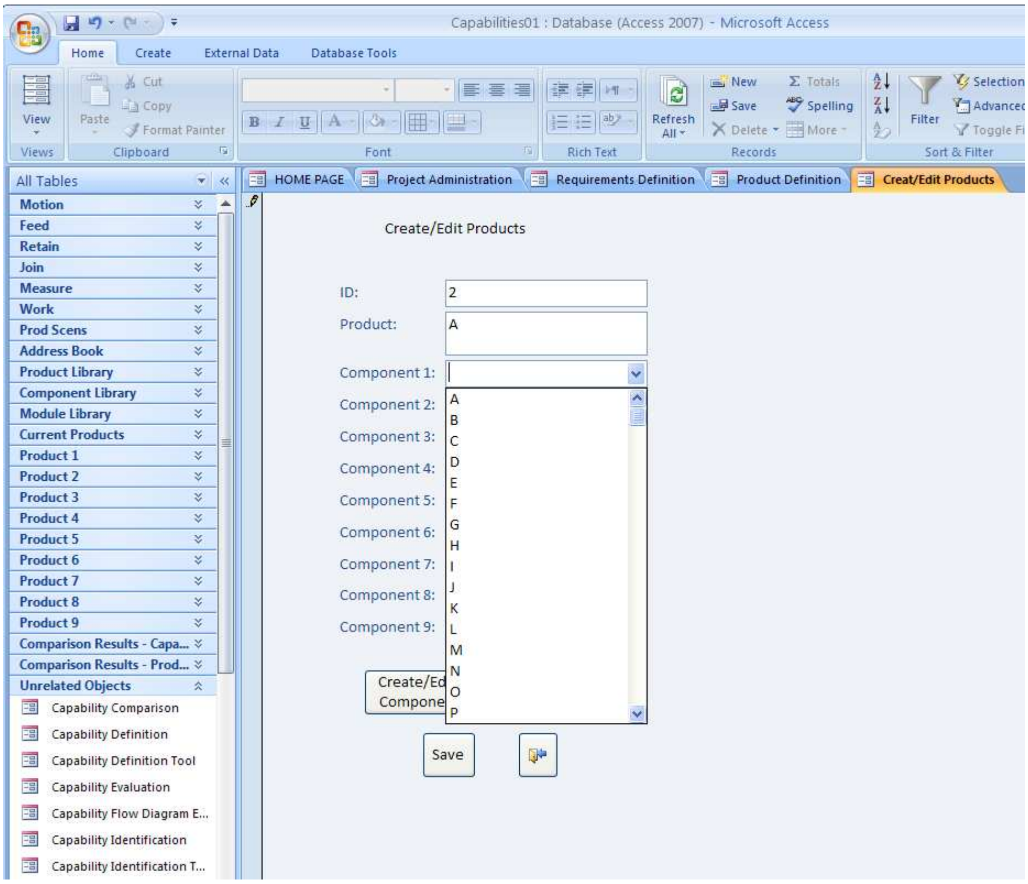
- Store, move and manipulate large volumes of numerical data
- Link to libraries of data
- Enable efficient upgrading and updating of the libraries
- Provide data processing and calculation functions
- Enable multiple users, potentially across multiple computing platforms, experience and locations
- Ensure wide and easy access

In satisfying the above requirements, it was decided to utilise Microsoft's Access (MSA) software package. MSA is available as part of the Microsoft Office application suite. It is a form of data and database management. It is widely accessible, also offering the potential to be web-based, thus giving the wide access and multiple users. MSA is also strongly linked to Excel, which enables large volumes of data to be added, removed and edited with comparative ease.

Further to these benefits, MSA can also run certain macros, which enable additional functionality, including data processing, to be included. Whilst the features of the macros are relatively limited, MSA also contains integrated Visual Basic programming functions to provide for more complex functionality. The following sub-sections outline and describe the application of MSA to CAMARA, specifically regarding the *Interface*, *Tools and Macros* and the *Integration Considerations*.

6.4.2 Application Details

6.4.2.1 Interface



Capabilities01 : Database (Access 2007) - Microsoft Access

Create/Edit Products

ID: 2

Product: A

Component 1:

Component 2:

Component 3:

Component 4:

Component 5:

Component 6:

Component 7:

Component 8:

Component 9:

Figure 6-18: Example screenshot of the CAMARA MSA application

The interface to the CAMARA MSA application uses a visual and functional approach in-line with the Windows XP operating system. Some example screenshots are shown in Figure 6-18. Full descriptive details of the software are provided in Appendix D.

A full sitemap to the CAMARA MSA application is provided in Figure 6-19. This sitemap illustrates the links between pages, which itself is based upon the sequence of the processes within CAMARA. The sitemap uses numerical denominators for the pages to aid in their further description and development.

1. Project Administration.			
2. Requirements Definition.			
	2.1. Team Definition		
		2.1.1. Add Contact	
	2.2. Project Definition		
		2.2.1.Create/edit Production Scenario	
	3. Product Definition		
		2.3.1.Create/edit Product	
			2.3.1.1. Create/edit Component
			2.3.1.2. Define Connections
	2.4. System Definition		
		2.4.1.Create/edit Module	
			2.4.1.1. Module Specification Tool
3. Capability Evaluation			
	3.1. Capability Identification		
		3.1.1.Capability Identification Tool	
			3.1.1.1. CFD Editor
	3.2. Capability Definition		
		3.2.1. Capability Definition Tool	
	3.3. Capability Comparison		
		3.3.1.Comparison Matrix	
	3.4. Capability Set Analysis		
4. Configuration Planning			
	4.1. Production Sequencing		
		4.1.1. Sequencing Tool	
			4.1.1.1. Comparison Matrix
	4.2. Equipment Allocation		
		4.2.1. Equipment Pool Viewer	
			4.2.1.1. Configuration Viewer
	4.3. System Lifecycle		
		4.3.1. Lifecycle Viewer	
		4.3.2. Performance Viewer	
		4.3.3. Cost Viewer	
		4.3.4. Exportation	

Figure 6-19: Sitemap of the CAMARA MSA application

6.4.2.2 Key Stages and Tools

The key stages of the software application are the same as for the CAMARA approach. Furthermore, it utilises a number of self-contained tools that are manifestations of various key elements of the CAMARA approach. These are summarised in Table 6-1, which lists each element and the associated section within this thesis.

Table 6-1: Summary of the CAMARA application elements and their respective descriptions within this thesis

Application Element	Related Thesis Section
Requirements Definition	5.1.2
Capability Identification	4.3.1
Capability Definition	4.3.2
Capability Comparison	4.3.3
Configuration Generation	4.3.3.3
Configuration Optimisation	5.3
Equipment Allocation	5.3.5
Production Sequencing	5.3.4
System Configuration Lifecycle	5.3.5.4

6.4.2.3 Considerations Towards Integration and Exploitation of Application

Ensuring that the CAMARA approach can be integrated within existing systems in organisations is a fundamental aspect of ensuring industrial uptake and realisation. In order to achieve this, the different features must be considered and how they will link to the existing systems for each stakeholder. With respect to inputting (i.e. information to be uploaded) these are:

- **Customer**; Project databases
- **Product Designer**; Product databases
- **Manufacturer**; Equipment and system databases
- **System Integrator**; Past solution databases, Integration effort and costs and Available system databases
- **Equipment Manufacturer**; Equipment databases

This highlights that the majority of information will come from databases operated by the various stakeholders. Thus, rather than requiring the manual entry of data (although this feature should be preserved as an option), there should exist the function to automate uploading.

In comparison, relatively little data needs to be extracted from the approach. The only stakeholder with requirements to export data from the CAMARA software would be the System Integrator, who would want to i) store the information regarding the solutions generated for future reference and ii) have use the selected configurations and sequence to define the integration project. The first point only requires that the information be exported to another database, but the second point is more complex. Whilst a database export would be sufficient, ideally the information should be linked to Project Management, Procurement and Design systems. However, integrating to this level of detail is outside of the scope of this thesis. A full description of each page, in sequential order of their use, is provided in Appendix D.

One of the fundamental benefits of using MSA as a basis for the CAMARA software is that it is possible to convert it to an internet accessible application. This enables collaboration between multiple users at multiple locations. It is intended that the users have controlled access, based upon their defined stakeholder role, to specific elements of the system. For example, a

Manufacturer would only be able to provide the details of the Available Equipment and contribute towards the definition of requirements. This has two primary benefits:

1. Preventing ‘information overload’. The entire software application contains a great number of individual pages and steps. This could be potentially daunting for an unfamiliar user, especially when they only have a limited role to play. Therefore, restricting access focuses them to the required tasks and improves both efficiency and acceptance.
2. Preventing ‘data mis-entry’. Any user may be inclined to enter information wherever they believe they be able to help. Regardless of how well-meaning or informed this information may be, it creates uncertainty where the purpose of the CAMARA approach is to eliminate it. Therefore by restricting user access to only that information which directly concerns them there can be no duplications, alterations or confusions.

Furthermore, MSA enables direct integration to the Microsoft Access and Excel programs, in terms of both importing and exporting data. This feature provides the potential for individuals and organisations to easily manipulate data stored in spreadsheets and databases and to then upload this directly into the application. This feature will enable time-efficient integration of the approach to existing equipment and product libraries. Furthermore, the functionality can be reversed by use of exporting, and so enables the results of the approach to be stored and used as part of legacy considerations. Thus, using the MSA software offers the ability to realise the majority of the required links.

6.5 Summary

This Chapter has provided descriptions of some of the key factors and technologies that will enable the CAMARA Tool to be realised.

- The Stakeholders involved in the specification and delivery of an RAS are represented by a new Stakeholder model, which encompasses six different roles and represents a complex relationship network.

- The elicitation of requirements is performed with respect to the Stakeholder model: the three identified groups of requirements identified are Product, Process and Project. Each group of requirements is attributed to a different stakeholder role.
- The link between the specified requirements and the capabilities, through the Capability Taxonomy, is established.
- The need and concept for Data Libraries is outlined with respect to Equipment, System/Solutions and Products. This supports the potential for intelligence and learning within the CAMARA Tool.
- It has been identified that Products and Equipment must be considered together in order for innovative processes to be developed, and for the up-scaling from prototyping to mass production volumes.
- The realisation of RAS and application of the capability-based approach has been assessed, particularly with respect to the Capability Identification and Definitions processes.
- The realisation of the CAMARA Tool within the software environment is achieved through the use of the Microsoft Access (MSA) program. The functionality is delivered through the implemented Macros and through separate tools programmed in Visual Basic. MSA also enables collaborative web-based development and solution generation.

7 Validation, Verification and Evaluation

7.1 Test Case 1 – Multiple Simple Products

To demonstrate the CAMARA method described in this thesis, a simplified example is used. This example is based on real equipment and processes, but considers a group of simple products so that, for the purposes of this thesis, it is easy to follow and concise. One of the key innovations of this research is the consideration of multiple reconfigurations (and therefore multiple products). The decision was made to generate an example which contains several products, but each with only a few processes.

The proposed methodology begins with the definition of the requirements. This assumes that the relevant data is available to accomplish this. If this is not the case then it will be necessary to acquire the data or to involve the relevant stakeholder in the definition process. In this case, all of the relevant data is known. For the purposes of clarity and conciseness, the full evidence for this test case is presented in Appendix E.

7.1.1 Define the Project

The project requirements must be defined – these are specifically the non-technical aspects of the requirements (typically financial and timescales). The definition of these requirements is fundamental to the definition of the Reconfiguration Scenario, which itself is important for the decision-making processes. The project requirements are collated – the information is gained directly from the relevant stakeholder (usually the Customer). In this case, the primary requirement from the Customer is to minimise cost and reconfiguration time. In addition, the customer is risk averse. Further specific details are:

- There is an existing assembly system and 5 required products.
- All of the products are required at the same time.
- There is a single operator representing all stakeholders.

7.1.1.1 Define the Reconfiguration Scenario

Because the customer has some specific requirements, there is no need to consider the boundary configurations in this case. The priorities from the customer are defined and therefore, the Reconfiguration Scenario is shown in Table 7-1.

Table 7-1: Reconfiguration Scenario for Test Case 1

Priority	**Score**
Cost	2 (High)
Performance	0 (Low)
Reconfiguration Time	2 (High)
Efficiency	0 (Low)
Risk	2 (High)
Total Score = 6	

It is noteworthy that this Reconfiguration Scenario is in fact the same as the Minimum Boundary Configuration. The suggested strategies for configuration optimisation are:

- *Maximise equipment re-use.*
- *Increase PMR; Select equipment modules that deliver processes for multiple products.*
- *Minimise cost of procured modules.*
- *Utilise 'familiar' equipment modules.*
- *Alter requirements (if necessary) so that the Priority Space plot falls within the 'Central Region'*

7.1.1.2 Validate Requirements

In order to validate that the defined requirements and priorities are compatible and that they are likely to deliver a realisable solution, the Requirement-Priority Tool should be implemented. However, in this case there is insufficient legacy data to create any usable plots, meaning that the stage must be missed.

7.1.2 Define the Existing System Capabilities

The example existing system consists of:

Module A: SCARA type robot

Module B: Mechanical gripper

Module C: A fixed tray for parts feeding

Module D: A static fixture for assembly.

7.1.2.1 Identify Existing Capabilities

Using the identification process described in Section 4.3.1.1, the following capabilities are identified:

- C_{EXA} (Robot) = Motion
- C_{EXB} (Gripper) = Retain
- C_{EXC} (Tray Feeder) = Feed
- C_{EXD} (Fixture) = Retain

Any further to this, an emergent capability is identified:

- C_{EXE} (Emergent: Robot + Gripper) = Join

Where;

C_{EXx} = *Capability of existing module x*

7.1.2.2 Define Existing Capabilities

At this stage the *General Capability Taxonomy,* described in Section 4.2.2, is used. The list of Existing Capabilities is thus:

- C_{EXA} = 1,1,39,2,2
- C_{EXB} = 3,1,2,2,2
- C_{EXC} = 2,3,2,2,1
- C_{EXD} = 3,2,2,2,3
- C_{EXE} = 4,1,2,2,2

7.1.3 Define the Product Requirements

The products used for this example are:

- Product A: Cap onto a Cylinder.
- Product B: Chip on a PCB.
- Product C: Pin on a Plate.
- Product D: Sphere onto a Shaft.
- Product E: Cube into a Slot.

Using the PFD Template, five PFDs are produced, one for each product. This enables the Capability Identification Tool to be used to identify all of the possible C_{RQ} for each product, as shown in Section 4.3.1. Thus the five Capability Sets can be listed and defined, which are shown in Appendix E.

7.1.4 Log Data in Comparison Matrix

The first task is to sequence the Capabilities. This is important for the selection and optimisation procedures later. Additionally, the capabilities are given a short alpha-numeric designator. These are shown in Appendix E.

Even a very simplified example of five two-part products results in a total of 55 required capabilities. This clarifies the need for the process to be automated within software. The sequenced Caps can then be entered into the Capability Matrix. The first stage of analysis investigates each configuration separately.

7.1.5 Perform Capability Comparison

Each Required Capability Set is compared to the Existing Capability Set. This is performed by asking the question “can this equipment perform this task?”. The Capability Comparison method is described in Section 4.3.3, whilst the results are presented in Appendix E.

From the results of the five comparison matrices, the following conclusions can be drawn with respect to the original equipment capabilities:

- The existing robot can be used in production of Products A, B, C and E
- The existing Tray Feeder cannot be used in production of any products
- The existing Mechanical Gripper can be used in production of Product B and E and possibly in the production of Products B and C
- The existing Fixture can be used in the production of Product E and possibly in the production of Products B and C
- The combination of the Robot and Gripper can be used in the production of Product A and possibly in the production of Products B, C and E.

In addition, the matrices identify which required capabilities cannot be met by the existing equipment. This is not summarised here for conciseness, instead the information is used directly in the Configuration Analysis.

7.1.6 Define the Three Capability Lists

After the comparison, the results are used to define the Three Capability Lists for each set. These are shown in Table 7-2.

Table 7-2: Summary of the three Capability Lists for the five sets for Test Case 1

Set A		**Set B**	
Capability List	**Capability**	**Capability List**	**Capability**
C_{SP} ($C_{EX\ldots}$)	B, C, D	C_{SP} ($C_{EX\ldots}$)	C
C_{PR} ($C_{RQA}\ldots$)	03 – 09, 11	C_{PR} ($C_{RQB}\ldots$)	03 – 06
C_{CN}	All remaining	C_{CN}	All remaining
Set C		**Set D**	
Capability List	**Capability**	**Capability List**	**Capability**
C_{SP} ($C_{EX\ldots}$)	C, E	C_{SP} ($C_{EX\ldots}$)	A – E
C_{PR} ($C_{RQC}\ldots$)	02 – 06, 08, 10,	C_{PR} ($C_{RQD}\ldots$)	01 – 11
C_{CN}	All remaining	C_{CN}	None
Set E			
Capability List	**Capability**		
C_{SP} ($C_{EX\ldots}$)	C		
C_{PR} ($C_{RQE}\ldots$)	03 – 06		
C_{CN}	All remaining		

7.1.7 Perform Individual Configuration Analysis

The first element of the configuration analysis is to analyse the configuration for each product independently. The Production Scenario has already been defined and the Configuration Optimisation strategies identified. Application of these results in the following configurations, where capabilities to be procured are represented by (C_{PR}), is shown in Appendix E.

Thus the 35 capabilities to be procured are found and listed. This list can then be addressed by the module allocation.

7.1.8 Configuration Validation

The configuration validation is performed and identifies that there is one invalid reconfiguration point:

- In Configuration C, C_{EXE} cannot be removed because it is emergent from C_{EXA} and C_{EXB}, both of which are required.

7.1.9 Module Allocation

The 35 capabilities to be procured are evaluated against the module library to identify the most suitable. As previously identified, the allocation strategy aims to minimise the number of new modules, so those modules that can deliver multiple capabilities (from the list of 35) are allocated first. The results of this are shown in Table 7-3. This table shows that a total of 13 additional modules satisfy 25 required capabilities. This is focussed primarily in the need for feeders as well as three retaining, one joining and one motion module.

Further to this, 10 required capabilities are identified as transportation (i.e. conveying) and so are not considered in this analysis. These being; C_{RQA} 03, C_{RQA} 04, C_{RQB} 03, C_{RQB} 04, C_{RQC} 03, C_{RQC} 04, C_{RQD} 03, C_{RQD} 04, C_{RQE} 03 and C_{RQE} 04.

This provides a realistic reflection of the true flexibility of components: motion systems, such as robots, are typically the most flexible modules, whilst feeders are the least (often requiring one feeder per product due to the subtle differences in components impacting the ability to feed them.

Table 7-3: List of the modules to be procured and the capabilities they satisfy

Procured Module	Module Type	Module Cap. Definition	Satisfied Req. Cap's
Mod F	Feeder	2.2.4.2.3	C_{RQA} 05, C_{RQA} 06
Mod G	Feeder	2.2.1.1.1	C_{RQB} 05
Mod H	Feeder	2.2.2.1.1	C_{RQB} 06
Mod J	Feeder	2.2.1.3.3	C_{RQC} 05
Mod K	Feeder	2.3.4.3.3	C_{RQC} 06
Mod L	Feeder	2.3.4.1.1	C_{RQD} 05
Mod M	Feeder	2.3.5.1.1	C_{RQD} 06
Mod N	Feeder	2.2.2.2.2	C_{RQE} 05, C_{RQE} 06
Mod O	Gripper	3.1.4.2.3	C_{RQA} 07, C_{RQA} 08, C_{RQB} 08, C_{RQD} 07
Mod P	Fixture	3.2.4.2.3	C_{RQA} 09, C_{RQD} 09
Mod Q	Gripper	3.1.5.1.1	C_{RQD} 08
Mod R	Joining	4.2.1.2.2	C_{RQA} 11, C_{RQC} 11, C_{RQD} 11
Mod S	Motion	1.1.31.3.2	C_{RQD} 01, C_{RQD} 02

7.1.10 Module Configuration and Layout

Based upon the module allocation results, the configurations can be updated with the list of specific modules and the required capabilities they deliver. This information can then be summarised into a list of the module types and the specific module delivering them for each of the configurations; this information is shown in Appendix E.

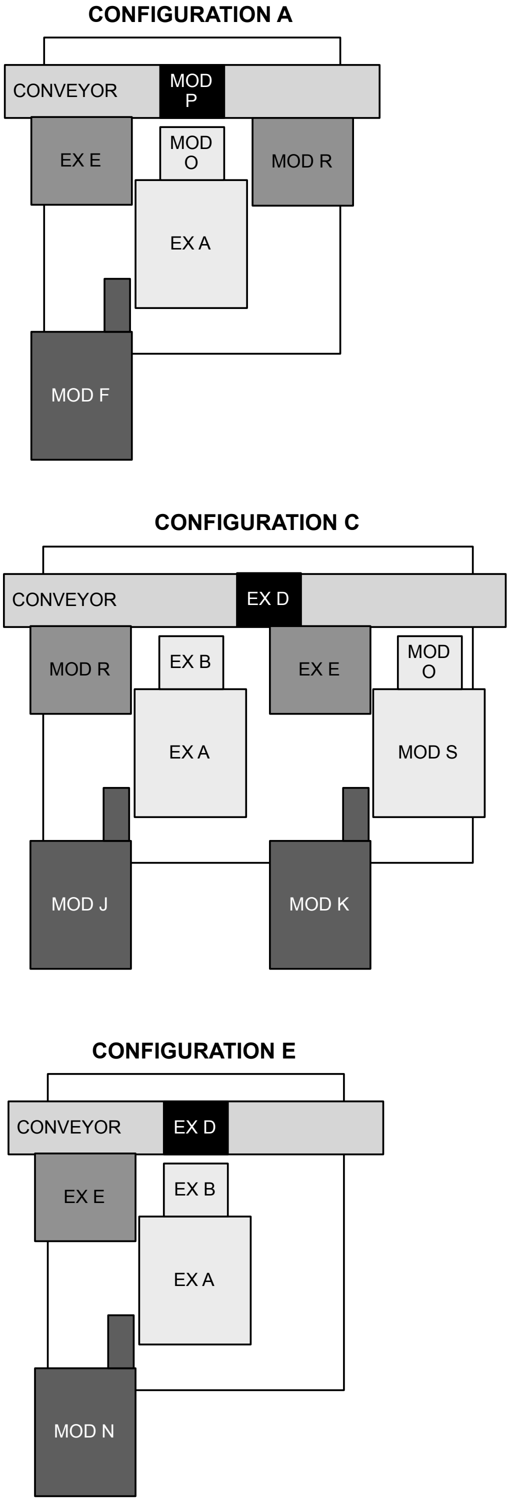


Figure 7-1: Schematics for each of the configurations for Test Case 1

In this test case, the main purpose is to minimise the number of modules to be procured. This is achieved in two ways. The first is to focus on modules that can offer as many of the required capabilities as possible during the search of the equipment database. The second is to compare the list of modules to be procured against the existing modules to see if any new modules can replace the existing ones. In this case, none of the new modules can completely replace the existing capabilities. Thus, the previously found information can then be used to create a schematic for each configuration (reference Figure 7-1).

7.1.11 Perform Sequence Analysis

The first element of the sequence analysis is to construct one amalgamated comparison matrix. All of the five sets are listed in a single matrix, this matrix is then extended vertically with a triangular "House of Quality" style inter-relationship grid. This is used to perform the same kind of comparison of capabilities as performed previously but between the different required sets. For example, in Table 7-4, Configurations a and B have 6 matching capabilities out of a possible 21.

Table 7-4: Summary of the Similarity Coefficients (in fractions)

	Existing	**Config'n A**	**Config'n B**	**Config'n C**	**Config'n D**	**Config'n E**
Existing	N/A	3/9	5/9	3/9	0/9	7/9
Config'n A	Repeat	N/A	6/21	9/21	6/21	6/21
Config'n B	Repeat	Repeat	N/A	8/21	6/21	13/21
Config'n C	Repeat	Repeat	Repeat	N/A	8/21	6/21
Config'n D	Repeat	Repeat	Repeat	Repeat	N/A	4/21
Config'n E	Repeat	Repeat	Repeat	Repeat	Repeat	N/A

Table 7-5: Summary of the Similarity Coefficients (in decimals)

	Existing	**Config'n A**	**Config'n B**	**Config'n C**	**Config'n D**	**Config'n E**
Existing	N/A	0.33	0.56	0.33	0	0.78
Config'n A	Repeat	N/A	0.29	0.43	0.29	0.29
Config'n B	Repeat	Repeat	N/A	0.38	0.29	0.62
Config'n C	Repeat	Repeat	Repeat	N/A	0.38	0.29
Config'n D	Repeat	Repeat	Repeat	Repeat	N/A	0.19
Config'n E	Repeat	Repeat	Repeat	Repeat	Repeat	N/A

With each capability compared, a ratio is derived to determine the similarity between the requirements (and hence the likely similarity between the resulting configurations). This is termed the Similarity Coefficient. The full matrix is not shown due to its size. Table 7-4 summarises the new comparison results in fractions whilst Table 7-5 displays the results in decimals.

Thus it can be seen that the four highest value Similarity Coefficients, ignoring repeats of the Existing Configuration, are:

Ex:E, B:E, A:C and B:C

As these first four coefficients do deliver a realisable sequence, the fifth relationship must be between the single occurrence configuration (again ignoring the Existing) and the remaining configuration, which is A:D. Thus the suggested sequence is:

Ex➔E➔B➔D➔C➔A

This analysis is based upon consideration of the Required Capabilities and this approach produces some points of note;

- The comparison is hugely influenced by ‘directionality’, i.e. depending on which capability you consider first, the result of the comparison may be different. For example, if two capabilities are identical apart from their accuracies when comparing from the higher accuracy capability there is a match, but comparing from the lower there is not. The solution implemented is to consider both directions simultaneously.
- The other point is that consideration only of the original required capabilities does not account for the actual module allocation. This can result in some significant differences, demonstrated by the re-consideration of the Production Sequence based on allocated modules.
- However, the consideration of modules then requires consideration of the actual layout and location of each module as it is assumed that moving a module from one location to another requires the same effort and downtime as replacing a module.

- Thus a visual inspection of the derived sequence is that it appears to be suitable and certainly a favourable reconfiguration route.
- The conclusion is that the Sequence Planning approach is suited to early capability-based analysis, but that a more advanced method of validation is required (reference Section 7.1.15).

7.1.12 Perform Configuration and System Projections

Sufficient information exists to enable calculations of Cost and Reconfiguration Time. Only if this information is suitable and compliant with the initially defined requirements will the final stage be moved to. The calculations can be performed at system or configuration level. For Cost, it is assumed that the total financial cost is the most important aspect. Additionally, it is complex to consider the cost of a module used in multiple configurations.

Total System Cost (κ_T):

$$\kappa_T = \Sigma\kappa_M + \Sigma\kappa_R$$

(κ_{Mx} = cost of module x, κ_{Ryz} = cost of reconfiguration between configuration y and configuration z)

Where (using Test Case 1, summarised in Table 7-6, as an example);

$$\Sigma\kappa_M = (\kappa_{MF} + \kappa_{MG} + \kappa_{MH} + \kappa_{MJ} + \kappa_{MK})$$

$$\Sigma\kappa_R = (\kappa_{R1\text{-}2} + \kappa_{R2\text{-}3} + \kappa_{R3\text{-}4} + \kappa_{R4\text{-}5})$$

For Reconfiguration Time, it is assumed that the total time for all reconfigurations is important but that it is also important to understand the breakdown for each reconfiguration.

Total Reconfiguration Time (T_{RT}):

$$T_{RT} = (T_{R1\text{-}2} + T_{R2\text{-}3} + T_{R3\text{-}4} + T_{R4\text{-}5})$$

Where:

$$T_{Rx\text{-}y} = (\Sigma T_{Csur} + \Sigma T_{Cmov} + \Sigma T_{Cpro})$$

7.1.13 Generate System Configuration Lifecycle

All of the information found in the preceding processes enables the generation of the complete System Configuration Lifecycle, which is summarised in Table 7-6. This information can then be integrated to the responsible stakeholder's existing procurement, project management and technical systems.

This gives a Total Reconfiguration Score (TRS) of:

- Number of module removals (M_R) = 11
- Number of module integrations (M_I) = 14
- Number of module moves (M_M) = 5

Table 7-6: System Configuration Lifecycle for Test Case 1

ACTION	SPECIFICS/NOTES
PROCURE MODULES	MOD F, MOD G, MOD H, MOD J, MOD K, MOD L, MOD M, MOD N, MOD O, MOD P, MOD Q, MOD R, MOD S
STOP PRODUCTION OF ***EXISTING CONFIG'N***	N/A
REMOVE MODULES FROM ***EXISTING CONFIG'N***	EX E
MOVE MODULES IN SYSTEM	NONE
INTEGRATE MODULES TO SYSTEM	MOD N
START PRODUCTION OF ***CONFIG'N E***	N/A
STOP PRODUCTION OF ***CONFIG'N E***	N/A
REMOVE MODULES FROM ***CONFIG'N E***	MOD N
MOVE MODULES IN SYSTEM	NONE
INTEGRATE MODULES TO SYSTEM	MOD G, MOD H
START PRODUCTION OF ***CONFIG'N B***	N/A
STOP PRODUCTION OF ***CONFIG'N B***	N/A
REMOVE MODULES FROM ***CONFIG'N B***	MOD G, MOD H
MOVE MODULES IN SYSTEM	EX E
INTEGRATE MODULES TO SYSTEM	MOD J, MOD K, MOD O, MOD R, MOD S
START PRODUCTION OF ***CONFIG'N C***	N/A
STOP PRODUCTION OF ***CONFIG'N C***	N/A
REMOVE MODULES FROM ***CONFIG'N C***	EX B, EX D, MOD J, MOD K, MOD S
MOVE MODULES IN SYSTEM	EX E, MOD O, MOD R
INTEGRATE MODULES TO SYSTEM	MOD F, MOD P
START PRODUCTION OF ***CONFIG'N A***	N/A
STOP PRODUCTION OF ***CONFIG'N A***	N/A
REMOVE MODULES FROM ***CONFIG'N A***	MOD A, MOD F
MOVE MODULES IN SYSTEM	EX E, MOD R
INTEGRATE MODULES TO SYSTEM	MOD L, MOD M, MOD Q, MOD S
START PRODUCTION OF ***CONFIG'N D***	N/A

Thus;

$$\mathbf{TRS = M_R + M_I + (2 \times M_M)}$$

$$\mathbf{TRS = 11 + 14 + (2 \times 5)}$$

$$\underline{\mathbf{TRS = 35}}$$

Manual validation has demonstrated that this value for the TRS cannot be improved. Thus it can be concluded that the Reconfiguration Sequencing enables the selection of the most efficient means of producing all of the required products.

7.1.14 Test Case 1 Conclusions

This test case has demonstrated a simplified example of the CAMARA method. It has shown that the approach can deliver realistic results and provide full traceability of the data and decisions made. Looking individually at each key stage in the approach, the primary issues that arise are:

- The entire Definition process would benefit from the use of standardised data entry forms.
- The Requirement Validation requires a significant volume of legacy data to implement. This is not always readily available.
- The Module Allocation process is hampered by a lack of real module data.
- The generation of the System Projections is limited by the data available concerning integration time, effort and cost.
- Overall, the issue of the large volume of data to be manipulated remains.

The majority of the approach worked as expected: the issues listed were not unexpected. However, whilst some issues are identified, a number of successes can be highlighted:

- The Capability Identification process provides a means for finding and subsequently defining both the required and available capabilities.
- Use of the Capability Taxonomy for the definition of capabilities is appropriate and the ability to upgrade or change taxonomies without

impacting the analysis approach is important for the scalability and applicability of CAMARA.

- The Reconfiguration Scenarios enables effective optimisation of configurations without substantial input or consideration of a variety of complex factors. This is further supported by the comparative ease with which results are achieved, thereby making multiple analysis cycles feasible.
- The Production Sequence Analysis offers an effective means of identifying the most efficient configuration sequence within the system.
- The TRS value provides a useful indicator of the overall effort required to realise all of the configurations. This value could be improved with consideration of weighting factors for removing and integrating (see Section 7.1.15).
- Overall, the Capability-Based analysis approach provides an effective means of assessing the feasibility of reconfigurations.

Within the scope of this thesis, it is not possible to acquire sufficient real and valid data for numerical analysis. So the focus of any remedial actions is on the overall method. In this case, the major point highlighted is that the use of CAMARA as a manual tool is very time-intensive and requires good data logging. Thus, for Test Case 2, the MSA software is implemented and trialled.

7.1.15 Proposed CAMARA Revisions

Based upon the work conducted in the calculation of Test Case 1, a number of potential improvements have been highlighted. The

Total Reconfiguration Score (TRS) Weighting. The concept of the TRS is to offer a means of quantifying the reconfiguration effort for a particular configuration sequence, thereby enabling the confirmation that the selected sequence is the most efficient.

In the Production Sequencing tool (reference Section 5.3.4) the TRS is calculated by considering module removal effort as being equal to module integration effort and that moving a module requires one removal and one integration. This is potentially an overly simplified view.

Whilst physically making and breaking connections may take broadly the same amount of effort, module integration may require a number of additional steps, such as ensuring the module is located precisely, teaching locations as well as the important step of testing the modules functionality. Allowing for this requires the inclusion of weighting factors in the TRS equation:

$$\mathbf{TRS = M_R + M_I + (2 \times M_M) = (M_R + M_M) + (M_I + M_M)}$$

Including weighting factors;

$$\mathbf{TRS = (\alpha \times (M_R + M_M)) + (\beta \times (M_I + M_M))}$$

Where;

$$\boldsymbol{\alpha} \textbf{ = module removal factor}$$

$$\boldsymbol{\beta} \textbf{ = module integration factor}$$

$$\boldsymbol{\alpha < \beta}$$

However, this equation then attributes the same level of effort to the integration of new modules, modules used before and to modules being moved. It is very likely that the effort in integrating and testing a module that was operating in the preceding configuration will be significantly less than that required for an entirely new module. The effort in integrating a previously used module (i.e. one that has been previously integrated, but is not present in the preceding configuration) will be less than new modules, but more than moving a present module. Thus, the equation can be refined to:

$$\mathbf{TRS = (\alpha \times (M_R + M_M)) + (\beta \times M_M) + (\gamma \times M_{IA}) + (\delta \times M_{IN})}$$

Where;

$$\mathbf{M_{IA}} \textbf{ = number of available module integrations}$$

$$\mathbf{M_{IN}} \textbf{ = number of new module integrations}$$

$$\boldsymbol{\beta} \textbf{ = integration factor for moved modules}$$

$$\boldsymbol{\gamma} \textbf{ = integration factor for integrated existing modules}$$

$$\boldsymbol{\delta} \textbf{ = integration factor for integrated new modules}$$

$$\boldsymbol{\beta < \gamma < \delta}$$

This form allows for the differences in integration effort for different *module statuses*, however it does not account for differences in *module class*. The effort in removing or integrating, for example, a gripper is likely to be substantially lower than for a robot. Thus it is proposed to have separate weighting factors for each of the six module classes:

$$\mathbf{TRS} = \{(\alpha_1 \times (M_{R1} + M_{M1})) + (\beta_1 \times M_{M1}) + (\gamma_1 \times M_{IA1}) + (\delta_1 \times M_{IN1})\} + \{(\alpha_2 \times (M_{R2} + M_{M2})) + (\beta_2 \times M_{M2}) + (\gamma_2 \times M_{IA2}) + (\delta_2 \times M_{IN2})\} + \ldots + \{(\alpha_6 \times (M_{R6} + M_{M6})) + (\beta_6 \times M_{M6}) + (\gamma_6 \times M_{IA6}) + (\delta_6 \times M_{IN6})\}$$

The equation above represents three of the six classes used in the capability taxonomy structure. Whilst it will better represent the true reconfiguration effort required, it also requires more detailed analysis and data management as well as requiring a large number of weighting factors to be defined.

Thus it is proposed that, for the purposes of simplicity, the CAMARA Tool calculate the TRS based on two weighting factors (α and β). It is proposed that the most complex TRS calculation be used only in final detailed projections in cases where optimising reconfiguration effort is of critical importance. In the majority of situations, the approximate calculation provides sufficient information for identifying the optimal production sequence.

7.2 Test Case 2 – Multiple Complex Products

7.2.1 Introduction

The main purpose of Test Case 2 is to demonstrate the elements of the approach that are significantly affected by the implementation of a more substantial application. The Test Case utilises more complex products that are derived from the 3D-M project as well as from other research activities.

The aspects of the approach most under consideration are within the Capability Model, specifically the Required Capabilities identification, definition and comparison. Test Case 1 used five products each with only two components. Whilst this test case is highly suitable for a relatively concise demonstration of the entire approach, it is not truly representative of microdevices. Therefore, any issues specifically associated with the volume of data and likely results from representative microdevices cannot be identified without the consideration of accurate microdevices.

Furthermore, one of the primary issues identified in Test Case 1 was the volume of data to be entered into the system. Therefore, a revised definition procedure is considered.

The full evidence supporting Test Case 2 is provided in Appendix F.

7.2.1.1 Test Case 2 Situation

Test Case 2 is built upon the scenario described in Section 3.5.2. In this situation, Company X has developed six different products that are all due to be clinically trialled prior to their approval for sale and mass production. All of the products are required only in small batches and so the priorities for the customer are to minimise reconfiguration effort and cost.

7.2.1.2 Existing System Specification

The existing (and available) equipment consists of the following:

• 1 x SCARA robot with auto tool changer	*ModA*
• 1 x 2 axis liner robotic stage with manual tool changer	*ModB*
• 1 x mechanical gripper, 3 fingered for cylindrical parts	*ModC*
• 1 x mechanical gripper, 4 fingered for cubic parts	*ModD*
• 1 x bowl feeder for cylindrical parts	*ModE*
• 1 x tray feeder for cubic parts	*ModF*
• 1 x 6-station conveyor unit	*ModG*

7.2.1.3 Product Specifications

The products are defined according to their constituent parts and the relationships between them – the liaisons. These are used to define the capabilities required in order to realise the assembly of the product. The six products considered are:

1. Camera Pill
2. Dispensing Pill
3. Diagnostics Pill
4. Fluid Separator
5. Micro Pump
6. Acoustic Amplifier

7.2.2 Consideration of Liaisons

The analysis of Test Case 2 considers a different approach in the specification and definition of both the required products and available system;

Liaisons. *Equipment Liaisons* are the connections between equipment modules and between the modules and the system framework. *Product Liaisons* are the connections between components within a product.

Equipment Liaisons are important in the Capability Identification and in the final realisation of a system. During Capability Identification, Equipment Liaisons can be used to identify Emergent Capabilities. During final realisation, the liaisons enable the System Integrator to plan the details of the integration of the modules.

Product Liaisons are a potential route for the identification and definition of the Required Capabilities. The Product Designer can define each component part within a product using the appropriate taxonomy. They can then identify all of the liaisons between components in that product and define them, again using the taxonomy. Then, the Product Designer must only identify the sequence in which components are brought in for the assembly sequence to be identified. Furthermore, the application of a few key rules enables the definitions made to support the definition of the capabilities without additional effort.

This step utilises the previously defined components and liaisons in accordance with the following rules, which leads to the creation and population of a table for each required product:

- Motion capabilities are dictated by;
    - System framework,
    - Final system layout,
    - Component Strength
    - Liaison Precision
- Feeding Capabilities are dictated by;
    - Relevant component factors
- Retaining Capabilities are dictated by;
    - Relevant component factors
- Joining Capabilities are dictated by
    - Relevant liaison definition

7.2.3 Other Considerations

Beyond the consideration of the liaisons, there are a number of other specific points investigated within this test case, including; *unknown values*, *repeated capabilities*, *reorientation of components* and the *six standard capabilities from the PFD*.

Unknown values may exist on either the product of equipment side. A value that cannot be specifically quantified may not be that unusual, hence the use of linguistic denominators for the taxonomies. However, in certain cases a particular characteristic may be completely unknown and so rather than making a guess that may give a false result at the comparison stage it is proposed to consider the value as unknown and denominate this with an ‘x’ in place of the number. This will have the consequence of preventing that capability from being an ‘exact match’ and increases the likelihood of a ‘possible match’. Furthermore, this concept can be extended to conditions where the capability can deliver any or all of the options within a characteristic.

Repeated capabilities are those capabilities that occur more than once in a configuration. For this to be the case, *the capabilities must have exactly the same purpose, not just the same definition*. An example would be where a component is gripped and placed on the fixture before being gripped again to be assembled or moved. For the purposes of this thesis, these repeats are ignored and only considered in the final system layout.

Component reorientation is a sub-set of the repeated capabilities described above. In this case however, the component may be subject to motion in additional degrees of freedom and so this may not actually be a repeated capability (however, it will be preceded at least by a repeat gripping capability). In this case, the reorientation is treated as a new motion capability and supported by any other relevant capabilities that are not repeats.

The six standard capabilities are those that are derived from the standard form of the PFD. These are:

I. Feed component x
II. Grip component x
III. Move component x

IV. Join component x to y

V. Fixture component x

VI. Convey fixture

Table 7-7: Summary of the derivation and rules for the six standard capabilities

Standard Capability	Description	Derived from	Rules
I	Feed component x	2.{Component Def'n}	
II	Grip component x	3.1.{Component Def'n}	
III	Move component x	System architecture	
IV	Join component x to y	4.{Liaison Def'n}	Value = 0 if V has value ≠ 0
V	Fixture component x	3.2.{Component Def'n}	Value = 0 if IV has value ≠ 0
VI	Convey fixture	System layout	Only occurs between workstations

These can all be, potentially, automatically generated from the definitions provided with respect to the products, liaisons, system architecture and the final layout. Extrapolating from the rules derived in Section 7.2.2, Table 7-7 is produced.

7.2.4 Test Case 2 Conclusions

In comparison to Test Case 1, Test Case 2 delivers far more accurate results. This is a direct result of the increase to the level of detail of the definition of Capability. This is demonstrable as the only change made to the TC was the Capability definition.

It should be noted that the addition definition criteria has resulted in additional specification efforts and so, whilst the results are more accurate, the effort to produce them has increased. This, however, is substantially outweighed by the quality of the results.

This test case has demonstrated a simplified example of the CAMARA method. It has shown that the approach can deliver realistic results and provide full traceability of the data and decisions made. Looking individually at each key stage in the approach, the primary issues that arise are:

- The more realistic volumes of data within Test Case 2 has demonstrated that data management tools are essential. However, complete automation of the process is still not desirable as it removes the true engineering understanding and the ability to make 'judgement calls' in marginal situations.

- Whilst the automation of capability definition appears to be efficient, it actually requires a more substantial definition effort up-front. Furthermore, the automatically defined capabilities will still need to be checked.
- The repeat capabilities are not a significant problem and are dealt with, but they further support the need for the tool to be human-driven.
- The creation of the six standard capabilities is a useful assistance and guide for the operator.

7.3 Test Case 3 – Development of Microdevices

7.3.1 Introduction

Section 6.3 described the need and drive to consider both Assembly Equipment and Microdevices in the development of innovative and integrated processes. This is a key enabler for the realisation of microdevice production, and a target of the 3D-M project. In order for microdevices to be realised within a modular system, it is necessary to ensure that automated processes can assemble them and that the relevant equipment can be integrated within a modular and reconfigurable environment.

In order to assess the influence of the CAMARA Tool and the potential for its application at the earliest phases of product development, it was decided to compare two methods: 'conventional' and CAMARA-assisted. In the first case, the investigation into the assembly processes was performed in the 'conventional' research manner. Then the CAMARA method was applied to the device and available equipment, and finally the results were compared.

This section introduces two innovative micro products that are test cases within the 3D-M project and the challenges associated in delivering them. It also discusses the impact of implementing them within an automated environment.

Descriptions of the assembly equipment utilised are provided in Appendix G. The full details of the devices, the assembly challenges the pose and the trials performed are provided in Appendix H.

7.3.2 Microdevice 1 – The Micro Probe

The micro-CMM probe presented here was developed at NPL to help realise the accuracy and traceability required; it is comprised of a solid shaft, a flexure assembly, and a probing sphere.

7.3.2.1 Micro Probe Design

The micro-CMM probe presented here was developed at NPL to help realise the accuracy and traceability required by the microscale and precision manufacturing industries [Haitjema, Pril and Schellekens, 2001].

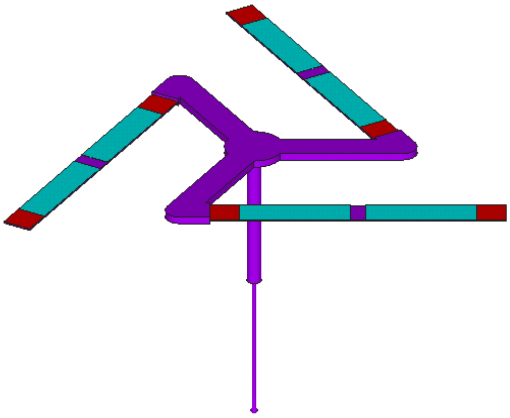


Figure 7-2: Image of the micro CMM probe, designed by NPL

The probe is comprised of a solid shaft, a flexure assembly, and a probing sphere. A 3D model of the device is shown in Figure 7-2. The shaft is manufactured from tungsten carbide (WC) via EDM and wire eroding. The flexure assembly is a laminar structure, manufactured by a micromachining process. The flexures include PZT actuators and sensors that are deposited onto the surface of the structure during the manufacturing process. The probing sphere attached to the end of the WC shaft is made of silica. The shaft is 200 μm in diameter where it joins the flexure and 70 μm in diameter where it joins the probing sphere. The shaft is connected at the thick end to the delicate piezoelectric flexure structure via a 100 μm diameter spigot. At the thin end a

100 μm diameter glass sphere is connected concentrically. These joints must be made without damaging any of the components, but special attention is placed on the protection of the sphere. The assembly requirements for the shaft onto the flexure specify a positional accuracy of ± 0.5 μm and the angle between the shaft and flexure to be 90° ± 0.29°. These factors are of primary importance in ensuring correct function of the final product.

7.3.2.2 Assembly Trials Conclusions

From the research conducted, several conclusions can be drawn:

- Implementing the Klocke nano precision workstation for alignment and insertion of the shaft and flexure parts is feasible. The equipment is capable of resolutions in excess of those required.
- Utilising the Zeiss NVision for micro scale assembly of components is a feasible application, primarily due to the dexterity and accuracy of the micro manipulators.
- Microspheres can be manipulated and manoeuvred without the need for damaging grippers; however, this results in a substantial increase in the required effort, time, and operator skill to complete.
- Using FIB deposition to join two micro components is not feasible due to the time frames and the need for access to all sides of the assembly.
- Using SEM glue to join two micro components is feasible, but the process requires development and refinement.

In order to facilitate the production of micro probes within an RAS and targeting the mass-production cycle time of 1-2 hours, the solutions must focus on consideration of the Klocke system and adhesive dispensing. Despite the considerable time-scales allowed for assembly, the use of the NVision is not feasible for a number of reasons:

- It is not possible to integrate within known RAS.
- The process required cannot be automated and requires continual operator involvement.

- The equipment and processing is particularly expensive. Whilst such financial commitments can be justified in some cases, the combination of low volumes and profit margins cannot support such investment.
- The conducted trials required significantly longer the 2 hours to achieve assembly. However, this hurdle could be overcome by a combination of process optimisation and parallelisation of equipment.

7.3.3 Microdevice 2 – The Micro Fluidics Device

The product is a microfluidics device consisting of several discs stacked on top of one another. The discs are 10mm in diameter and 1mm thick, a CAD model of one of the discs with the joint feature is shown in Figure 7-3. They are manufactured through a micro-injection moulding process from a suitable polymer; Polymethyl methacrylate (PMMA). PMMA is a transparent thermoplastic, used frequently in place of glass; it is selected due to the ease of processing both in moulding and in ultrasonic welding. Furthermore, the transparency enables the path of a (coloured) fluid to be inspected without the need for destructive testing.

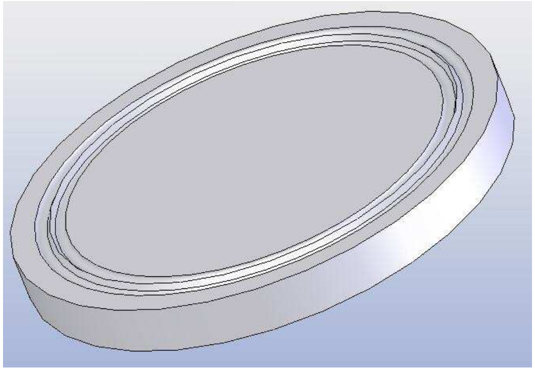


Figure 7-3: Image of the CAD model used to produce the discs with single side joint feature

7.3.3.1 Assembly Challenges

Whilst the discs are relatively large, the gap *between the layers* must not exceed 20µm as each disc contains a number of micro channels which cross the boundary between the layers. Simulations have demonstrated that a gap of less than 20μm will result in little of the fluid entering the gap and thus will have a negligible effect on the performance of the device.

7.3.3.2 Microfluidics Conclusions

The conducted research has demonstrated that the USW process is suitable for joining of flat face features with micro-scale features. However, it has also highlighted that the flash trap is larger than necessary to contain the molten material. It also suggested that the flash trap may be inducing secondary welding of the parts at the outer edges of the trap.

7.3.4 Microdevice Capability Analysis

This detailed level of analysis into the assembly processes and challenges faced provides a suitable foundation for the application of the Capability Model. Through evaluation these products at the conceptual level, it should be possible to predict what type of equipment capabilities are required. This enables the user to determine whether the challenge is within the realms of conventional assembly systems or within the research domain. The list of capabilities required for the delivery of microdevice 1 is shown in Table 7-8 and for microdevice 2 in Table 7-9.

The required capabilities for these two test cases, using the microassembly taxonomy, are shown in Section 4.2.3. When compared against the existing and available assembly equipment, it becomes clear that no complete technological solution is available. Therefore, assembly of the devices requires either i) the development of new and/or improved processing capabilities, or ii) the redesign of the product such that they can be delivered by conventionally. The * denotes capabilities that are repeated. This is due to the composition of Microdevice 2 from 5 identical parts, thus the required assembly operations and associated capabilities are identical.

Table 7-8: List of the Required Capabilities for Microdevice 1

Cap Locator	Cap Designator	Cap Definition
MD101 – MD102	C_{RQMD1} 01	1,2,2,3,1,1,3,2,2
MD102 – MD104	C_{RQMD1} 02	1,2,2,3,1,1,3,2,2
MD103 – MD104	C_{RQMD1} 03	1,2,2,3,1,1,3,2,2
MD104 – MD106	C_{RQMD1} 04	1,2,2,3,1,1,3,2,2
MD105 – MD106	C_{RQMD1} 05	1,2,2,3,1,1,3,2,2
MD101	C_{RQMD1} 06	2,1,3,3,1,3,1,1,2,2
MD103	C_{RQMD1} 07	2,4,2,1,4,3,1,1,2,2
MD105	C_{RQMD1} 08	2,4,1,4,4,3,1,1,2,2
MD101	C_{RQMD1} 09	3,1,3,3,1,3,1,1,2,2
MD102	C_{RQMD1} 10	3,1,3,3,1,3,1,1,2,2
MD103	C_{RQMD1} 11	3,4,2,1,4,3,1,1,2,2
MD104	C_{RQMD1} 12	3,4,2,1,4,3,1,1,2,2
MD105	C_{RQMD1} 13	3,4,1,4,4,3,1,1,2,2
MD106	C_{RQMD1} 14	3,4,1,4,4,3,1,1,2,2
MD102	C_{RQMD1} 15	4,1,3,1,1,2,2,2,2,2
MD104	C_{RQMD1} 16	4,2,3,3,1,1,2,2,2,2
MD106	C_{RQMD1} 17	4,2,3,3,1,1,2,2,2,2

Table 7-9: List of the Required Capabilities for Microdevice 2

Cap Locator	Cap Designator	Cap Definition
MD201 – MD202	C_{RQMD2} 01	1,1,3,1,1,1,1,2,1
MD202 – MD204	C_{RQMD2} 02	N/A
MD203 – MD204	C_{RQMD2} 03	1,1,3,1,1,1,1,2,1*
MD201	C_{RQMD2} 04	2,3,2,4,2,1,1,1,2,1
MD203	C_{RQMD2} 05	2,3,2,4,2,1,1,1,2,1*
MD201	C_{RQMD2} 06	3,3,2,1,2,1,1,1,2,1
MD202	C_{RQMD2} 07	3,3,2,1,2,1,1,1,2,1*
MD203	C_{RQMD2} 08	3,3,2,1,2,1,1,1,2,1*
MD204	C_{RQMD2} 09	N/A*
MD202	C_{RQMD2} 10	4,1,2,1,1,2,2,2,2,1
MD204	C_{RQMD2} 11	4,2,3,3,2,2,2,2,2,1*

7.3.5 Conclusions from Microdevice Investigations

One of the most important results from the microdevice investigations is that the consideration of the Reconfiguration Scenario in the earliest phases of product development is highly important in arriving at a suitable manufacturing process. By only considering the likely Reconfiguration Scenario after production feasibility has been demonstrated, that demonstration work is substantially undermined.

Furthermore, this point highlights the particular challenges of microdevice production: one device has a cycle time in excess of 1 hour, whilst the other has a cycle time of less than 15 seconds. This variation in the term ‘mass production’ has significant impact in the selection and integration of processes.

Evaluating and understanding existing and available assembly capabilities, both with regards to pure functionality and to throughput rates, and comparing this to the needs of new and potential products offers manufacturers the ability to select and implement the production activities that best fit their needs.

The limitation is that the approach may simply identify that it is not possible to deliver the requirements with existing technologies. Thus the solution must be found through R&D activities. A conclusion is that the concept of the inclusion of TRLs within the CAMARA should be considered.

7.4 Test Case Comparison

The three test cases have provided validation of the concepts presented in this thesis. More specifically, they have enabled different aspects of the work to be explored and evolved. Test Case 1 used a heavily simplified set of products to demonstrate the overall process, with a particular focus on the Capability Model. However, whilst the simplification enabled a rapid assessment of the overall process, aspects of the reconfiguration planning could not be explored as the individual configurations were not representative of real systems. This test case was applied at a relatively early stage of work and the results were fundamental to several changes made to CAMARA that were validated in the second test case.

Test Case 2 was developed in order to investigate specific features within the process and to validate the modified approach. The entire CAMARA process was conducted in order to achieve valid results, and this demonstrated the importance of data management as the volume of data was significant. It also illustrated that the revisions had enabled a simplified and more accurate method of data acquisition (through component liaisons) as well as standardising the approach towards all capabilities. The focal points for the results were the reconfigurations generated and the evaluation of them – particularly the reconfiguration validation and sequencing processes.

These test case products were developed within the 3DM project and as a result of the consultations described in Section 3.5.1. The products in Test Case 1 are representative of common assembly processes. They were chosen specifically as a series of products that would be typically delivered through entirely different equipment – therefore any commonalities identified by CAMARA can be seen as a successful re-use of resources that otherwise would have been wasted.

The products in Test Case 2 were developed directly from the 3DM project products. They were simplified and key functional data removed as this is not relevant to their assembly. As with Test Case 1, this group was expanded with the intention of ensuring that the group would never be considered as deliverable by anything other than a series of entirely different assembly systems.

Test Cases 1 and 2 have focussed on the application of CAMARA *from the capabilities*. Test Case 3 approaches the problem from another angle; by focussing on the application of CAMARA *from the hardware*. This is second method is more representative of how equipment suppliers and product designers will perceive CAMARA. It also demonstrated the application within the specific issues directly associated with the micro domain – these being represented by the true micro nature of the two products and the processing equipment used to deliver them.

All of these test cases have focussed within the micro domain and have shown that, at an abstract level, there is little additional challenge presented. However, at a detailed technical level, microdevices pose a significant additional challenge. This has been represented in an adapted Capability Taxonomy specific to the micro domain (reference Appendix A).

7.5 Research Discussion

The research presented in this thesis was conducted in order to support the implementation and further understanding of Reconfigurable Assembly Systems and their delivery of mircodevices. The work is part of the larger body of research conducted within the 3D-Mintegration project, specifically the Micro Assembly work package, and supports its key aims.

After reviewing the available literature (presented in Chapter 2) it was concluded that there remained a significant gap in the scientific knowledge related to the planning and delivery of multiple products through a reconfigurable assembly system. Furthermore, there was a particular lack of consideration of the micro domain. These gaps were specified and an overall approach to address them outlined in Chapter 3. Anecdotal evidence from 3D-M partners, as well as equipment manufacturers and research colleagues, suggested that there exists a ‘void’ between conventional mini products and innovative nano products in which many developmental microdevices sit. This ‘void’ is formed by the inability of miniaturised conventional processes and equipment to deliver the required scales and precisions, whilst nanotechnologies cannot perform for such (relatively) large components. Essentially, microdevices are often too small for mini systems but too large for nano systems.

This conclusion is, in part, supported by the process development work presented in Chapters 6 and 7. Two of the 3D-M test case products were selected for evaluation and process development. The microfluidics device was shown to be producible through innovative application of existing technologies and processes. However, the smaller microprobe device has been shown to be more complex to deliver – neither of the two investigated approaches are fully satisfactory in addressing all of the requirements. The work has demonstrated that the issues of production time and equipment cost continue to be prohibitive in the area of microdevices. The significant risks and costs associated with microdevices further supports the hypothesis that RAS offer a potential solution to the challenges of microdevice assembly.

One of the key challenges associated with the specification of assembly systems is that of comparing the requirements, which are derived from the products, to the potential solutions, which are derived from the equipment. This research presents the use of Capabilities as a means of defining these requirements and availabilities such that they can be directed compared and assessed for compatibility. This definition is achieved through a Capability

Taxonomy and separate definition processes. The taxonomy developed and presented in this thesis focuses in enabling consideration of the production of the device as early in the design process as possible. This will offer substantial benefits to the manufacturer and will support cost reduction. This is achieved through the use of linguistic variables rather than requiring exact numbers – thus the product and components can be defined within the approach without the designs having been finalised. Hence, RAS specification can be performed in tandem with product development.

The Capability Model (presented in Chapter 4) developed enables a structured comparison of the availabilities and requirements and generation of the boundary configurations, which highlight the minimum and maximum reconfiguration effort and cost required. This further supports the early consideration of the assembly system by presenting the range of options that are available. In addition, this ‘quick-look’ approach may assist in the DFA processes by exposing the implications of design changes.

The challenge of capability-based analysis is to ensure it produces results that can be applied in reality. To this end, a Reconfiguration Methodology has been developed with the purpose of converting capability-based configuration definitions into specific equipment-oriented specifications. Further to this, the nature of reconfigurable systems is that they have an existing configuration. As such, the existing equipment is considered preferentially over equipment that must be procured. The challenge of balancing the requirements, customer priorities, available equipment and procurable equipment is a complex one and is dealt with in this research by the application of the Reconfiguration Methodology (presented in Chapter 5). Specifically, the Reconfiguration Scenario concept, the Requirements-Priority Tool and equipment allocation and validation processes. It is through the decomposition of the problem into individual elements that solutions are found – this is particularly important as this work is focussed on multiple products and thus multiple configurations.

The research has also demonstrated that there are significant volumes of data that must be managed and processed. The relevant stakeholders are modelled and their role within the approach determined to manage the flow of information into and out of the approach. Further to this, test case 1 (presented in Chapter 7) demonstrated that the significant amount of data to be managed and processed makes manual application of the approach very time-consuming, which negates many of the benefits. Thus the data flow and storage is defined and benefits from the application of a software programme.

This work has demonstrated the feasibility and functionality of a tool that supports and structures the complex process that results in a specified assembly system reconfiguration. It is focussed in situations where multiple reconfigurations are required and an RAS is implemented. Importantly, the tool does not propose that there is a single, ideal system solution for a given problem; the input and experience of the system integrator is an important factor alongside the customer’s requirements and the products to be delivered. The use of legacy system libraries is important in this and forms the potential for learning, and even self-learning within the tool.

7.6 Summary

This Chapter has presented a number of Test Case applications, representing various aspects of the enabling of RASs within the micro manufacturing domain.

Test Case 1 considered a series of simple products to demonstrate and evaluate the CAMARA approach. This work showed that the approach offers a structured path for deriving the optimal configurations and their sequence. In conjunction with the details of the RAS architecture, this enables a system integrator to generate a detailed costing and timescale plan and to realise the systems.

Test Case 2 considered a more complex situation involving products with more parts and thus a greater required capability set. The demonstrated work focussed on the key aspects of the overall approach most affected by this increase in capabilities.

Test Case 3 considered the assembly of two innovative microdevices from the 3D-M project. This work focussed on the issues presented in the prototyping and delivery of microdevices and the impact that these have on production within an automated environment.

From these cases, a number of specific conclusions can be drawn:

- Overall, the CAMARA approach enables the operator to generate the probable optimal configurations for each product and the most efficient sequence in which to use them.
- However, even in the most simple of cases, the volume of data to be considered, stored and processed is too great for a manually operated tool to be efficient.
- The additional complexity added by products with a higher number of component parts manifests itself primarily in:
    - Logging of the required capabilities
    - Capability comparison
    - Module allocation
- The use of a software programme is more important to manage and trace the information used – it is still important for the software user (who is expected to be a system integrator) to be able to make or control the decisions.
- Delivering microdevices, at any production volume, is a significant technological challenge. The cost, complexity and time required to develop microdevices are clear inhibitors to their transition to market. Continued development of micro-scale assembly technologies, primarily joining processes, is required.
- The use of conceptual-level analysis and projection of the required assembly system is potentially important in risk mitigation in research and development environments and is a potential avenue for expansion of the CAMARA tool.

8 Conclusions

The purpose of this thesis was to contribute to the knowledge in the field of manufacturing engineering by working towards a framework for the configuration of modular assembly systems. The developed approach and methodologies are combined into the CAMARA Tool, which offers multiple users the ability to collaboratively realise a series of reconfigurations of a modular assembly system.

In conjunction with this, an integrated capability taxonomy will enable products and equipment to be evaluated, compared and specified without any prior prejudices having an influence on the result. This is an important facet in identifying the optimal solution to each problem. However, this taxonomy should be integrated within the knowledge structure and the processes and also be ‘open’: i.e. editable and upgradeable. The integration within the methodology will enable more effective synergies with the product and system design processes, it will also enable users to store capability-based data thereby linking past experiences by the core capabilities involved rather than the human-interpreted similarities. This should offer more reliable re-use of designs. An editable and upgradeable capability taxonomy should allow users to alter the details of the taxonomy to suit the processes and equipment used, as well as allowing for the specific modular architecture of the system.

The capability model facilitates structured decision-making for the determination of individual configurations through the comparison of the required (product associated) capabilities and the existing and available (equipment associated) capabilities. The difference between ‘existing’ and ‘available’ capabilities is that existing are the capabilities associated to the equipment currently installed within the existing line whilst available are any equipment modules within the equipment library. After the specification of each configuration, it is prudent to validate and optimise. In a multi-product, multi-configuration system, the optimisation of configurations should occur at two levels: *individual configuration level* to ensure the product and process requirements are met, and *total system level* to ensure that the project requirements are met. The different classes of requirements are detailed in

Section 4.2.1. Once the configurations have been validated and optimised, the performance and cost of the system should be projected, based on the available data, and the systems configuration lifecycle forecast, which can be integrated into existing management and procurement systems allowing for seamless realisation of the conceptual designs.

It can also be noted that the research presented in this thesis could be considered within the overall area or axiomatic design. Whilst the work has broadly adhered to the two axioms of requirements and information independence and CAMARA overall follows the transformation through the four domains, the approach cannot be considered to be truly axiomatic in nature.

The reported work aims to address some of the challenges inherent in the realisation of such a methodology and the associated tools. This chapter discusses the fundamental ideas and assumptions and outlines how this work proposes to address the identified knowledge gaps. Specifically, the following sections provide a general overview of the methodology itself and its requirements. Furthermore, this section outlines the hypotheses, assumptions and the research approach used during the investigation. The fundamental aspects and features of the methodology are also presented.

8.1 Limitations

The work conducted within this thesis and the results achieved have been limited. The primary limitation was that a System Integrator was not directly involved in the implementation of the test cases. This meant that the results obtained could not be compared with what would have been delivered by conventional means. Whilst this issue does mean that the absolute accuracy of the system cannot be confirmed, it does not detract from the overall benefit of the approach itself. This limitation has additionally led to a lack of legacy data that would enhance application of CAMARA.

The other limitation is that CAMARA has only been applied to test cases with a relatively consistent scale – both with respect to the size of components assessed and the volume of capabilities considered. For true scalability of the approach to be assessed, a broader range of application cases is needed.

However, it can be suggested that the overall principles were unaffected by the scaling that does exist within this work, and thus could be scaled up or down as needed. This is facilitated by the abstraction of the capability concept and the independence of the taxonomy.

8.2 Achievements

This thesis has presented the work conducted in addressing the overall aim and individual objectives. Chapters 4, 5 and 6 have described the research conducted and detailed aspects of the CAMARA methodology. Chapter 7 has presented demonstrations and validations of the approach. The Appendices have variously supported these Chapters. The original research objectives, as defined in Chapter 1, are:

- To develop a new Capability Model to enable the identification, definition and comparison of capabilities.
- To formulate a Capability Taxonomy, which will provide a standard and structured definition of ‘capability’.
- To propose a Reconfiguration Methodology to enable configurations to be evaluated, specified and validated.
- To develop a number of Auxiliary Functions that will support the overall approach.
- To Validate the developments and proposals through the utilisation of a number of test cases that are to be derived from research projects.

An innovative **Capability Model** has been developed. This model enables the identification, definition and comparison of the capabilities associated with the required products and the available system.

The *Capability Identification Method* enables reliable identification of capabilities from the specific products and equipment through the implementation of a structured approach with defined rules. The *Capability Definition* is performed using the Capability Taxonomy in conjunction with sequenced guidance provided in the model itself. The *Capability Comparison* is performed through the application of the developed Comparison Matrix.

This identifies the missing, redundant and matching capabilities and also enables the generation of the minimum and maximum reconfigurations.

This model is supported by a newly-defined **Capability Taxonomy**. The developed taxonomy utilises a hierarchical structure and linguistic variables rather than requiring specific numerical values.

Through this structure, both the products and equipment can be described using the same terminology, with the specificities of the definition process provided by the Capability Model. In addition, the definition can be made without the designs having been finalised and so enabling specification to be performed in tandem with product development.

An innovative **Reconfiguration Methodology** has been developed. This enables the conversion of capability-based configuration definitions into specific equipment-oriented specifications.

It uses the results drawn from the Capability Model to deliver a *System Configuration Lifecycle* that can be used to identify the key stages and actions required to deliver the different system configurations. This methodology is supported by an evaluation of the requirements and priorities associated with assembly systems and by the encapsulation of these requirements into a *Reconfiguration Scenario* that guides the reconfiguration and equipment module allocation processes. This also leads into the *Configuration Generation and Optimisation*. Further to this, the *Requirements-Priority Tool* enables the evaluation of the requirements themselves; providing an assessment of the feasibility of the any produced solution. Through the evaluation of the configuration capabilities, the *Production sequencing method* enables the determination of the optimal sequence of configurations, which ensures that the reconfiguration effort across the system life is minimised.

Several **Auxillary Functions**, which support the application of CAMARA, have been developed. A new *Stakeholder and Communication Model* has been proposed. The relevant stakeholders are modelled and their role within the approach determined to manage the flow of information. The stakeholder model is utilised to structure the involvement of the several parties with interests in the collaborative development of the assembly system.

Microassembly equipment and processes, within the context of a reconfigurable assembly environment, have been considered and developed. Microdevice production is supported through the development of the processes and equipment that deliver micro assembly and reconfigurable systems. The delivery of two test case products from the 3DM project has been used to exemplify this.

The overall approach has been demonstrated as workable and realisable through the consideration of a series of *Test Cases*. These have demonstrated the overall functionality of CAMARA using a simplified series of products, highlighted specific aspects and demonstrated the MSA software using more complex products and the evaluation and development of the processes and solutions to deliver microdevices.

8.3 Future Work

The proposed taxonomy provides the baseline for the definition of assembly capabilities and offers the potential for customisation and extension into further areas of application. The research conducted has centred on assembly processes and as such this has been reflected in the taxonomy developed. Future customisation from this baseline would enable the approach to be applied to wider or more specific areas of manufacturing.

Many processes in the micro domain are in their infancy with respect to both the understanding of their mechanisms and principles and the development of the associated equipment. As such, micro assembly processes themselves need to be better understood and the equipment delivering them matured in order for the potential of microdevices to be realised.

The additional complexities presented by reconfiguring an assembly system multiple times is currently not considered by cost models. The development of a reconfiguration-focussed cost model, potentially with consideration of customisation functions for individual stakeholders, is proposed. This would provide greater clarity of the financial implications as well as give more reliable business cases, thereby increasing potential industrial uptake.

Finally, the work presented in this thesis has the potential to be expanded into a number of additional areas. These include multi-line evaluation, system error/failure recovery and lifetime extension. Multiple systems could be evaluated by the application of the methodology with an altered balance of required and available capabilities. System failures could be recovered from by an analysis of the remaining capabilities and the original requirements. System lifetimes could be extended through an altered application of the proposed methodology by the consideration of promoting component longevity.

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11 Appendix A: Full Capability Definition Information

11.1 Tables Supporting the Definition of the Micro Taxonomy

Table 11-1: Detailed definition table for Move class of the Micro Assembly Taxonomy

Move Class		
Characteristic	**Option**	**Indicative Value**
DoF	High	5 – 6
	Medium	2 – 4
	Low	1
Stroke	High	>750mm
	Medium	250-750mm
	Low	<250mm
Repeatability	High	<0.5µm
	Medium	0.5-5µm
	Low	>5µm
Payload	High	>10g
	Medium	1-10g
	Low	<1g
Speed	High	>1000mm/s
	Medium	100-1000mm/s
	Low	<100mm/s
Fragility	High	*tbc*
	Medium	*tbc*
	Low	*tbc*
Clean room compatible?	Yes	*{select one}*
	No	*{select one}*
Vacuum compatible?	Yes	*{select one}*
	No	*{select one}*

Table 11-2: Detailed definition table for Retain class of the Micro Assembly Taxonomy

Retain Class		
Characteristic	**Option**	**Indicative Value**
Part Shape	Plate	plate-like
	Box	box-like
	Disc	disc-like
	Cylinder	cylinder-like
	Complex	other shape
Part Size	High	>1mm
	Medium	0.1-1mm
	Low	<0.1mm
Stroke	High	>750mm
	Medium	250-750mm
	Low	<250mm
Repeatibility	High	<0.5µm
	Medium	0.5-5µm
	Low	>5µm
Payload	High	>10g
	Medium	1-10g
	Low	<1g
Speed	High	<0.1s
	Medium	0.1-1.0s
	Low	>1.0s
Fragility	High	*tbc*
	Medium	*tbc*
	Low	*tbc*
Clean room compatible?	Yes	*{select one}*
	No	*{select one}*
Vacuum compatible?	Yes	*{select one}*
	No	*{select one}*

Table 11-3: Detailed definition table for Join class of the Micro Assembly Taxonomy

Join Class		
Characteristic	**Option**	**Indicative Value**
Reversibility	Yes	*{select one}*
	No	*{select one}*
Repeatibility	High	<0.5µm
	Medium	0.5-5µm
	Low	>5µm
Joint strength	High	<0.5µN
	Medium	0.5-5µN
	Low	>5µN
Speed	High	<0.1s
	Medium	0.1-1s
	Low	>1s
Medium	Yes	*{select one}*
	No	*{select one}*
Thermal process	Yes	*{select one}*
	No	*{select one}*
Conductivity	Yes	*{select one}*
	No	*{select one}*
Clean room compatible?	Yes	*{select one}*
	No	*{select one}*
Vacuum compatible?	Yes	*{select one}*
	No	*{select one}*

Table 11-4: Detailed definition table for Feed class of the Micro Assembly Taxonomy

Feed Class		
Characteristic	**Option**	**Indicative Value**
Part Shape	Plate	plate-like
	Box	box-like
	Disc	disc-like
	Cylinder	cylinder-like
	Complex	other shape
Part Size	High	>1mm
	Medium	0.1-1mm
	Low	<0.1mm
Orientation – about horizontal	∞	no orientation
	4	4 correct angles
	2	2 correct angles
	1	1 correct angle
Orientation – about vertical	∞	no orientation
	4	4 correct angles
	2	2 correct angles
	1	1 correct angle
Fragility	High	*tbc*
	Medium	*tbc*
	Low	*tbc*
Payload	High	>10g
	Medium	1-10g
	Low	<1g
Speed	High	<0.1s
	Medium	0.1-1s
	Low	>1s
Clean room compatible?	Yes	*{select one}*
	No	*{select one}*
Vacuum compatible?	Yes	*{select one}*
	No	*{select one}*

11.2 DFA Taxonomy

		CHARACTERISTICS (Ch)							
CLASS		**Ch1**		**Ch2**		**Ch3**		**Ch4**	
		Type		*DoF*		*Max Precision*		*Max Range*	
Motion	1,	Move	1,	x	plus 1,	Low	1,	Low	1,
		Convey	2,	y	plus 2,	Medium	2,	Medium	2,
				z	plus 4,	High	3,	High	3,
				A	plus 8,				
				B	plus 16,				
				C	plus 32,				
		Type		*Part Type*		*Part Size*		*Robustness*	
Feed	2,	In-line	1,	Plate	1,	Small	1,	Low	1,
		Bulk	2,	Box	2,	Medium	2,	Medium	2,
		Sorted	3,	Disc	3,	Large	3,	High	3,
				Cylinder	4,				
				Sphere	5,				
		Type		*Part Type*		*Part Size*		*Robustness*	
Retain	3,	Grip	1,	Plate	1,	Small	1,	Low	1,
		Fixture	2,	Box	2,	Medium	2,	Medium	2,
				Disc	3,	Large	3,	High	3,
				Cylinder	4,				
				Sphere	5,				
		Type		*Medium*		*Precision*		*Mechanism*	
Join	4,	Reversible	1,	Yes	1,	Low	1,	Flat surface	1,
		Irreversible	2,	No	2,	Medium	2,	Insertion	2,
				Either	3,	High	3,	Pin-in-hole	3,
								Ridge-in-hole	4,
								Docking	5,
		Type		*Units*		*Precision*			
Measure	5,	Geometry	1,	Select from		Low	1,		
		Performance	2,	(dynamic list)		Medium	2,		
		Characteristic	3,			High	3,		
		Type		*Precision*		*Select from…*			
Work	6,	Material add		Low	1,	List (dynamic)			
		Material subtr		Medium	2,				
		Finishing		High	3,				

11.3 Micro Assembly Taxonomy

		CHARACTERISTICS (Ch)																	
CLASS		**Ch1**		**Ch2**		**Ch3**		**Ch4**		**Ch5**		**Ch6**		**Ch7**		**Ch8**		**Ch9**	
		DoF		*Stroke*		*Repeatibility*		*Payload*		*Speed*		*Fragility*		*Clean room compatible?*		*Vacuum compatible?*			
Motion	1,	Low	1,	Low	1,	Low	1,	Low	1,	Low	1,	Low	1,	No	1,	No	1,		
		Medium	2,	Medium	2,	Medium	2,	Medium	2,	Medium	2,	Medium	2,	Yes	2,	Yes	2,		
		High	3,	High	3,	High	3,	High	3,	High	3,	High	3,						
		Part Shape		*Part Size*		*Orientation about horizontal*		*Orientation about vertical*		*Fragility*		*Payload*		*Speed*		*Clean room compatible?*		*Vacuum compatible?*	
Feed	2,	Plate	1,	Low	1,	One	1,	One	1,	Low	1,	Low	1,	Low	1,	No	1,	No	1,
		Box	2,	Medium	2,	Two	2,	Two	2,	Medium	2,	Medium	2,	Medium	2,	Yes	2,	Yes	2,
		Disc	3,	High	3,	Four	3,	Four	3,	High	3,	High	3,	High	3,				
		Cylinder	4,			∞	4,	∞	4,										
		Complex	5,																
		Part Shape		*Part Size*		*Stroke*		*Repeatibility*		*Payload*		*Speed*		*Fragility*		*Clean room compatible?*		*Vacuum compatible?*	
Retain	3,	Plate	1,	Low	1,	Low	1,	Low	1,	Low	1,	Low	1,	Low	1,	No	1,	No	1,
		Box	2,	Medium	2,	Medium	2,	Medium	2,	Medium	2,	Medium	2,	Medium	2,	Yes	2,	Yes	2,
		Disc	3,	High	3,	High	3,	High	3,	High	3,	High	3,	High	3,				
		Cylinder	4,																
		Complex	5,																
		Reversibility		*Repeatibility*		*Joint Strength*		*Speed*		*Medium*		*Thermal process?*		*Conductivity?*		*Clean room compatible?*		*Vacuum compatible?*	
Join	4,	Yes	1,	Low	1,	Low	1,	Low	1,	Yes	1,	Yes	1,	Yes	1,	No	1,	No	1,
		No	2,	Medium	2,	Medium	2,	Medium	2,	No	2,	No	2,	No	2,	Yes	2,	Yes	2,
				High	3,	High	3,	High	3,										
		Type		*Precision*															
Measure	5,	Geometry	1,	Low	1,														
		Performance	2,	Medium	2,														
		Characteristic	3,	High	3,														
		Type		*Precision*															
Work	6,	Material add	1,	Low	1,														
		Material subtr	2,	Medium	2,														
		Finishing	3,	High	3,														

11.4 Detailed Taxonomy

		CHARACTERISTICS (Ch)															
CLASS		**Ch1**		**Ch2**		**Ch3**		Ch4		Ch5		Ch6		Ch7		Ch8	Ch9
		Type		*DoF*		*Max Precision*		*Max Range*		*Max Speed*		*P per DoF*		*R per DoF*		*Full Path desc*	*Full Perf desc*
Motion	1,	Move	1,	x	plus 1,	Low	1,	Low	1,	Low	1,	Low	1,	Low	1,		
		Convey	2,	y	plus 2,	Medium	2,	Medium	2,	Medium	2,	Medium	2,	Medium	2,		
				z	plus 4,	High	3,	High	3,	High	3,	High	3,	High	3,		
				A	plus 8,												
				B	plus 16,												
				C	plus 32,												
		Type		*Part Type*		*Part Size*		*Part Profile*		*Robustness*		*PPM*		*Orientation*		*Full part desc*	*Full perf desc*
Feed	2,	In-line	1,	Plate	1,	Small	1,			Low	1,	Low	1,	x	plus 1,		
		Bulk	2,	Box	2,	Medium	2,			Medium	2,	Medium	2,	y	plus 2,		
		Sorted	3,	Disc	3,	Large	3,			High	3,	High	3,	z	plus 4,		
				Cylinder	4,									A	plus 8,		
				Sphere	5,									B	plus 16,		
														C	plus 32,		
		Type		*Part Type*		*Part Size*		*Part Profile*		*Robustness*		*Orientation*		*Full part desc*		*Full perf desc*	
Retain	3,	Grip	1,	Plate	1,	Small	1,			Low	1,	x	plus 1,				
		Fixture	2,	Box	2,	Medium	2,			Medium	2,	y	plus 2,				
				Disc	3,	Large	3,			High	3,	z	plus 4,				
				Cylinder	4,							A	plus 8,				
				Sphere	5,							B	plus 16,				
												C	plus 32,				
		Type		*Medium*		*Precision*		*Mechanism*		*Materials*		*Mech load*		*Pressure Seal*		*Full connect des*	*Full parts desc*
Join	4,	Reversible	1,	Yes	1,	Low	1,	Flat surface	1,	Metal	1,	Low	1,	Low	1,		
		Irreversible	2,	No	2,	Medium	2,	Insertion	2,	Polymer	2,	Medium	2,	Medium	2,		
				Either	3,	High	3,	Pin-in-hole	3,	Composite	3,	High	3,	High	3,		
								Ridge-in-hole	4,	Mix	4,						
								Docking	5,								
		Type		*Units*		*Precision*		*Full test desc*									
Measure	5,	Geometry	1,	Select from		Low	1,										
		Performance	2,	(dynamic list)		Medium	2,										
		Characteristic	3,			High	3,										
		Type		*Precision*		*Select from…*											
Work	6,	Material add		Low	1,	List (dynamic)											
		Material subtr		Medium	2,												
		Finishing		High	3,												

12 Appendix B: Example of the Elimination Methodology

12.1 Introduction

Table 12-1: A Comparison Matrix, populated with an example application

			C_{REQ}																
C_{EX}			Motion			Feed		Retain			Join			Measure			Work		**Total b**
			a1	a2	a3	a4	a5	a6	a7	a8	a9	a10	a11	a12	a13	a14	a15	a16	
	Motion	b1	1	0.1	1														2.1
		b2	0	1	0.1														1.1
		b3	0	0	0														0
	Feed	b4				1	0.1												1.1
		b5				0	1												1
	Retain	b6						1	1	0									2
		b7						0	1	0									1
		b8						0	0.1	0									0.1
	Join	b9									1	0	0						1
		b10									1	0	0						1
		b11									0	0.1	1						1.1
	Measure	b12												1	0.1	1			2.1
		b13												0	1	1			2
		b14												0	0	0			0
	Work	b15															0	0	0
		b16															0	0	0
	Total a		1	1.1	1.1	1	1.1	1	2.1	0	2	0.1	1	1	1.1	2	0	0	

The *Elimination Methodology*, described in Section 5.3.1.3, is used to find an efficient configuration solution that uses as many *Existing Capabilities* (C_{EX}) as possible to deliver the *Required Capabilities* (C_{RQ}), whilst maintaining a PMR as close to '1' as possible. This approach is foreseen to be one of the more common applications as it seeks to strike a balance between absolute efficiency of the solution and maximised equipment re-use. The methodology is described below through the application of a simplified example. This example is based around a selection of capabilities – the exact details are not relevant to the illustration of the process.

The Comparison Matrix is populated during the Capability Modelling phase (see Table 12-1) and as a result the *3 Capability Lists* are generated. These are *Surplus Capabilities* (C_{SP}), *Procured Capabilities* (C_{PR}) and *Consideration Capabilities* (C_{CN}). Thus the Capability Lists for the matrix in Table 12-1 are:

C_{SP} = **b3, b14, b15, b16**
C_{PR} = **a8, a10, a15, a16**
C_{MT} = **0**
C_{CN} = **a1, a2, a3, a4, a5, a6, a7, a9, a11, a12, a13, a14, b1, b2, b4, b5, b6, b7, b8, b9, b10, b11, b12, b13**

As described in Section 4.3.3, the aim of the Reconfiguration analysis is to move all of the capabilities from the *Consideration* list into one of the two other existing lists or into the new *Matching Capabilities* (C_{MT}) list. This may not always be possible at this stage – the partial matches will require further analysis and so, unless they are eliminated during the process, will remain in the C_{CN} list.

The implementation of the Elimination Methodology, the specific application of which is shown below, results in the following lists being generated:

Capability Lists Status:

C_{SP} = **b3, b8, b10, b14, b15, b16**
C_{PR} = **a3, a8, a10, a14, a15, a16**
C_{MT} = **b1:a1, b2:a2, b4:a4, b5:a5, b6:a6, b7:a7, b9:a9, b11:a11, b12:a12, b13:a13**
C_{CN} = **0**

Step 1: The Comparison matrix is populated with Capabilities and the comparison performed (within the Capability Model).

Step 2: The **C_{SP}** and the C_{PR} lists are generated by elimination of any capabilities = 0, shown in Table 12-2.

Table 12-2: Comparison Matrix showing step 2 of the Elimination Methodology

	C_{REQ}																		
C_{EX}			Motion			Feed		Retain			Join			Measure			Work		**Total b**
			a1	a2	a3	a4	a5	a6	a7	~~a8~~	a9	a10	a11	a12	a13	a14	~~a15~~	~~a16~~	
	Motion	b1	1	0.1	1														2.1
		b2	0	1	0.1														1.1
		~~b3~~	~~0~~	~~0~~	~~0~~														~~0~~
	Feed	b4				1	0.1												1.1
		b5				0	1												1
	Retain	b6						1	1	~~0~~									2
		b7						0	1	~~0~~									1
		b8						0	0.1	~~0~~									0.1
	Join	b9									1	0	0						1
		b10									1	0	0						1
		b11									0	0.1	1						1.1
	Measure	b12												1	0.1	1			2.1
		b13												0	1	1			2
		~~b14~~												~~0~~	~~0~~	~~0~~			~~0~~
	Work	~~b15~~															~~0~~	~~0~~	~~0~~
		~~b16~~															~~0~~	~~0~~	~~0~~
	Total a		1	1.1	1.1	1	1.1	1	2.1	~~0~~	2	0.1	1	1	1.1	2	~~0~~	~~0~~	

Capability Lists Status:

C_{SP} = b3, b14, b15, b16

C_{PR} = a8, a10, a15, a16

C_{MT} = -

C_{CN} = a1, a2, a3, a4, a5, a6, a7, a9, a11, a12, a13, a14, b1, b2, b4, b5, b6, b7, b8, b9, b10, b11, b12, b13

Step 3: Each of the C_{EX} is then 'assigned' a C_{RQ}. This is achieved by addressing each C_{EX} in turn down the matrix and, when moving along the row, assigning to it the first CRQ encountered with a 'High match' i.e. a comparison value of '1' (see Table 12-3). This is progressed for all of the capabilities; however a CRQ cannot be assigned more than once.

Table 12-3: Comparison Matrix showing step 3 of the Elimination Methodology

	C_{REQ}																		
			Motion			Feed		Retain			Join			Measure			Work		**Total b**
			a1	a2	a3	a4	a5	a6	a7	~~a8~~	a9	a10	a11	a12	a13	a14	~~a15~~	~~a16~~	
C_{EX}	Motion	b1	1	0.1	1														2.1
		b2	0	1	0.1														1.1
		~~b3~~	~~0~~	~~0~~	~~0~~														~~0~~
	Feed	b4				1	0.1												1.1
		b5				0	1												1
	Retain	b6						1	1	~~0~~									2
		b7						0	1	~~0~~									1
		b8						0	0.1	~~0~~									0.1
	Join	b9									1	0	0						1
		b10									1	0.1	0						1.1
		b11									0	0	1						1
	Measure	b12												1	0.1	1			2.1
		b13												0	1	1			2
		~~b14~~												~~0~~	~~0~~	~~0~~			~~0~~
	Work	~~b15~~															~~0~~	~~0~~	~~0~~
		~~b16~~															~~0~~	~~0~~	~~0~~
	Total a		1	1.1	1.1	1	1.1	1	2.1	~~0~~	2	0.1	1	1	1.1	2	~~0~~	~~0~~	

Capability Lists Status:

C_{SP} = b3, b14, b15, b16

C_{PR} = a8, a10, a15, a16

C_{MT} = b1:a1, b2:a2, b4:a4, b5:a5, b6:a6, b7:a7, b9:a9, b11:a11, b12:a12, b13:a13

C_{CN} = a3, a10, a14, b8, b10

Step 4: The Matrix is then updated (see Table 12-4):

Table 12-4: Comparison Matrix showing step 4 of the Elimination Methodology

			C_{REQ}																
			Motion			Feed		Retain			Join			Measure			Work		**Total b**
			~~a1~~	~~a2~~	a3	~~a4~~	~~a5~~	~~a6~~	~~a7~~	~~a8~~	~~a9~~	a10	~~a11~~	~~a12~~	~~a13~~	a14	~~a15~~	~~a16~~	
C_{EX}	Motion	~~b1~~	~~1~~	~~0.1~~	~~1~~														~~2.1~~
		~~b2~~	~~0~~	~~1~~															~~1.1~~
		~~b3~~	~~0~~	~~0~~	~~0~~														~~0~~
	Feed	~~b4~~				~~1~~	~~0.1~~												~~1.1~~
		~~b5~~				~~0~~	~~1~~												~~1~~
	Retain	~~b6~~						~~1~~	~~1~~	~~0~~									~~2~~
		~~b7~~						~~0~~	~~1~~	~~0~~									~~1~~
		b8						~~0~~	~~0.1~~	~~0~~									0
	Join	~~b9~~									~~1~~	~~0~~	~~0~~						~~1~~
		b10										0.1	~~0~~						0.1
		~~b11~~									~~0~~	~~0~~	~~1~~						~~1~~
	Measure	~~b12~~												~~1~~	~~0.1~~	~~1~~			~~2.1~~
		~~b13~~												~~0~~	~~1~~	~~1~~			~~2~~
		~~b14~~												~~0~~	~~0~~	~~0~~			~~0~~
	Work	~~b15~~															~~0~~	~~0~~	~~0~~
		~~b16~~															~~0~~	~~0~~	~~0~~
	Total a		~~1~~	~~1.1~~	0	~~1~~	~~1.1~~	~~1~~	~~2.1~~	~~0~~	~~2~~	0.1	~~1~~	~~1~~	~~1.1~~	0	~~0~~	~~0~~	

Capability Lists Status:

C_{SP} = b3, b14, b15, b16

C_{PR} = a8, a10, a15, a16

C_{MT} = b1:a1, b2:a2, b4:a4, b5:a5, b6:a6, b7:a7, b9:a9, b11:a11, b12:a12, b13:a13

C_{CN} = a3, a10, a14, b8, b10

Step 5: The lists are then updated with any ‘zero-value’ capabilities that have emerged as a result of the eliminations identified (see Table 12-5):

Table 12-5: Comparison Matrix showing step 5 of the Elimination Methodology

			C_{REQ}																
C_{EX}			Motion			Feed		Retain			Join			Measure			Work		**Total b**
			~~a1~~	~~a2~~	a3	~~a4~~	~~a5~~	~~a6~~	~~a7~~	~~a8~~	~~a9~~	a10	~~a11~~	~~a12~~	~~a13~~	a14	~~a15~~	~~a16~~	
	Motion	~~b1~~	~~1~~	~~0.1~~	~~1~~														~~2.1~~
		~~b2~~	~~0~~	~~1~~															~~1.1~~
		~~b3~~	~~0~~	~~0~~	~~0~~														~~0~~
	Feed	~~b4~~				~~1~~	~~0.1~~												~~1.1~~
		~~b5~~				~~0~~	~~1~~												~~1~~
	Retain	~~b6~~						~~1~~	~~1~~	~~0~~									~~2~~
		~~b7~~						~~0~~	~~1~~	~~0~~									~~1~~
		b8						~~0~~	~~0.1~~	~~0~~									0
	Join	~~b9~~									~~1~~	~~0~~	~~0~~						~~1~~
		b10										0.1	~~0~~						0.1
		~~b11~~									~~0~~	~~0~~	~~1~~						~~1~~
	Measure	~~b12~~												~~1~~	~~0.1~~	~~1~~			~~2.1~~
		~~b13~~												~~0~~	~~1~~	~~1~~			~~2~~
		~~b14~~												~~0~~	~~0~~	~~0~~			~~0~~
	Work	~~b15~~															~~0~~	~~0~~	~~0~~
		~~b16~~															~~0~~	~~0~~	~~0~~
	Total a		~~1~~	~~1.1~~	0	~~1~~	~~1.1~~	~~1~~	~~2.1~~	~~0~~	~~2~~	0.1	~~1~~	~~1~~	~~1.1~~	0	~~0~~	~~0~~	

Capability Lists Status:

C_{SP} = b3, b14, b15, b16

C_{PR} = a8, a10, a15, a16, a3, a14, b8

C_{MT} = b1:a1, b2:a2, b4:a4, b5:a5, b6:a6, b7:a7, b9:a9, b11:a11, b12:a12, b13:a13

C_{CN} = a10, b10

Step 6: Pair together any capabilities with 'Low Match' i.e. a comparison score of '0.1'. As with Step 3, starting with the top C_{EX} and pairing it with the first encountered C_{RQ}, following the same sequential approach through the matrix (see Table 12-6).

Table 12-6: Comparison Matrix showing step 6 of the Elimination Methodology

			C_{REQ}																
			Motion			Feed		Retain			Join			Measure			Work		**Total b**
			~~a1~~	~~a2~~	~~a3~~	~~a4~~	~~a5~~	~~a6~~	~~a7~~	~~a8~~	~~a9~~	a10	~~a11~~	~~a12~~	~~a13~~	~~a14~~	~~a15~~	~~a16~~	
C_{EX}	Motion	~~b1~~	~~1~~	~~0.1~~	~~1~~														~~2.1~~
		~~b2~~	~~0~~	~~1~~															~~1.1~~
		~~b3~~	~~0~~	~~0~~	~~0~~														~~0~~
	Feed	~~b4~~				~~1~~	~~0.1~~												~~1.1~~
		~~b5~~				~~0~~	~~1~~												~~1~~
	Retain	~~b6~~						~~1~~	~~1~~	~~0~~									~~2~~
		~~b7~~						~~0~~	~~1~~	~~0~~									~~1~~
		~~b8~~						~~0~~	~~0.1~~	~~0~~									0
	Join	~~b9~~									~~1~~	~~0~~	~~0~~						~~1~~
		b10										0.1	~~0~~						0.1
		~~b11~~									~~0~~	~~0~~	~~1~~						~~1~~
	Measure	~~b12~~												~~1~~	~~0.1~~	~~1~~			~~2.1~~
		~~b13~~												~~0~~	~~1~~	~~1~~			~~2~~
		~~b14~~												~~0~~	~~0~~	~~0~~			~~0~~
	Work	~~b15~~															~~0~~	~~0~~	~~0~~
		~~b16~~															~~0~~	~~0~~	~~0~~
	Total a		~~1~~	~~1.1~~	0	~~1~~	~~1.1~~	~~1~~	~~2.1~~	~~0~~	~~2~~	0.1	~~1~~	~~1~~	~~1.1~~	0	~~0~~	~~0~~	

Capability Lists Status:

C_{SP} = b3, b14, b15, b16

C_{PR} = a8, a10, a15, a16, a3, a14, b8

C_{MT} = b1:a1, b2:a2, b4:a4, b5:a5, b6:a6, b7:a7, b9:a9, b11:a11, b12:a12, b13:a13

C_{CN} = a10:b10

Step 7: Updating the Matrix now empties it so the method now stops, leaving the following lists:

Capability Lists Status:

C_{SP} = b3, b14, b15, b16

C_{PR} = a8, a10, a15, a16, a3, a14, b8

C_{MT} = b1:a1, b2:a2, b4:a4, b5:a5, b6:a6, b7:a7, b9:a9, b11:a11, b12:a12, b13:a13

C_{CN} = a10:b10

The *Elimination Methodology* has been successful in minimising the C_{CN} list that requires further consideration as well as clearly identifying the solution configuration. Thus the analysis can, in this case, move on to the next phase.

12.2 Notes on the 4 lists and Elimination Methodology

During the elimination process (exemplified in Step 3 above) the first encountered ‘High match’ is taken and used in the solution configuration. However, the C_{EX} may in fact have several matches and so it is possible that the most efficient solution is not found.

For example; it would be inefficient to link a complex motion C_{EX} with a 1DoF motion C_{RQ} capability and then have to procure another 4DoF motion capability. Instead, it would be best to link the complex motion C_{EX} to the most complex motion capability and procure a 1DoF motion capability.

To address this issue, the population of the Comparison Matrix must not be random but instead be controlled and structured. Essentially, this would entail entering the capabilities in descending order of degree of complexity within each of the 6 classes. It is then important to ensure that during the elimination process the capabilities are addressed in that order; i.e. from top-left to bottom-right. This will maximise the efficiency of the reconfiguration at an early stage in the analysis.

13 Appendix C: Details of Equipment and Integration

13.1.1.1 Existing Platform Framework

The Framework utilised for this development work is the Feintool Modutec system (reference Figure 13-1). This is the State-of-the-Art in industrially applicable modular manufacturing, which enables equipment modules to be reconfigured in around 15 minutes; this is facilitated by standardised mechanical, electrical, control and service connections. Within the specific platform under investigation, the conveying system has been integrated: the Montrac system from Montech (reference Figure 13-2). This approach uses powered shuttles to convey the products along a fixed monorail. This system is far quieter and consumes only 5% of the energy used by a conventional belt conveyor. It has the added advantage of being able to provide power directly to the product carrier throughout the process.

Figure 13-1: Image of the Modutec System. (Courtesy of Feintool Automation)

Figure 13-2: Image of the Montrac System. (Courtesy of Montech)

13.1.1.2 Module and Process Integration

In order to effectively and safely integrate a number of process modules from a variety of suppliers, it is necessary to have a common and coherent design. However, the design and integration effort can be minimised by utilising an RAS with a consistent and defined architecture. In the case of the employed platform, it has a total of 8 bays. Ideally, each bay will contain one process. However, it is possible for one bay to contain multiple processes (through careful design and coordination) and also for one process to use two bays. Each bay consists of two areas: Process space and Controller space. These are located in the front half of the platform. The conveyor and supply distribution (of Ethernet, power and compressed air) are contained in the rear half (reference Figure 13-3 and Figure 13-4).

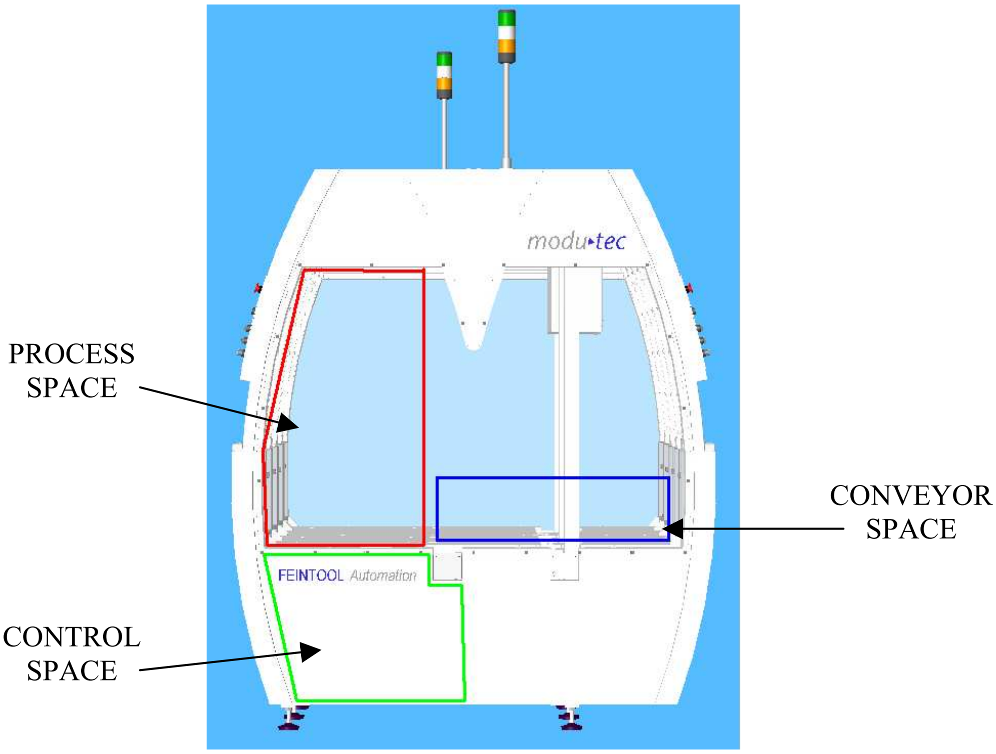


Figure 13-3: End view of platform with working areas highlighted

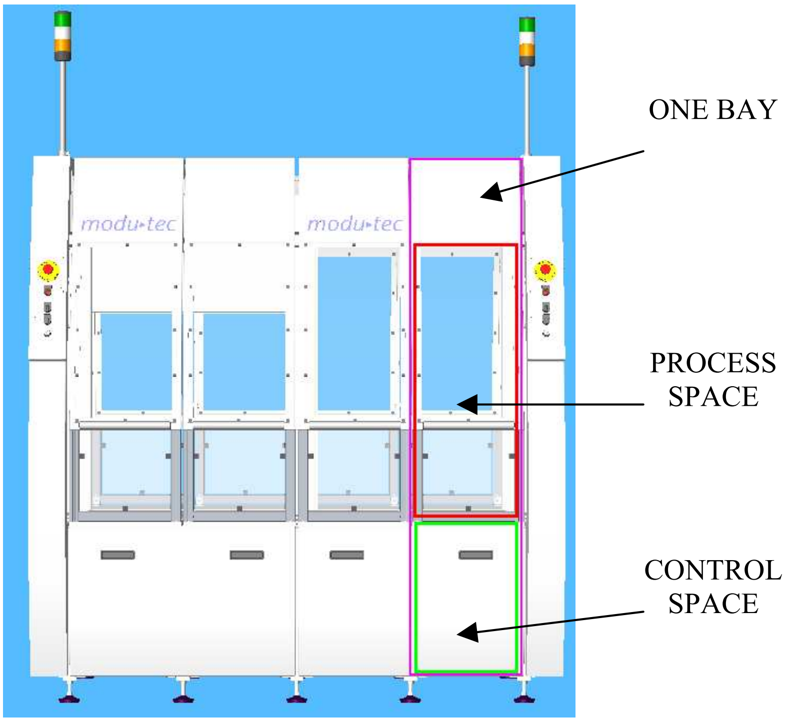


Figure 13-4: Side view of platform with working areas highlighted

13.1.1.3 Consideration of Functional Modules

One of the critical aspects in the implementation of RAS is for appropriate equipment modules to be available. In this sub-section, a series of equipment modules are addressed individually and considered for integration within the RAS described in Section 13.1.1.1. Each module is briefly described before the key attributes affecting potential integration into an RAS are assessed and the capabilities it offers identified and defined. In each case, the focus is in the micro domain and so the Micro Capability Taxonomy is used.

Klocke Nanotechnik 3 DoF Linear System

The Klocke Nanotechnik Linear Assembly System (Klocke) is a self-contained nanometre resolution system and comprises of three linear actuators with an additional actuator used to drive a gripper (see Figure 13-5). Table 13-1 summarises the system as both motion and gripping modules.

Table 13-1: Summary of the Klocke Linear System module

Equipment	Klocke Nanotechnik 3DoF Linear System	
Functionality	Assembly system	
Integration Issues	Limited access to working area, Lack of external I/O communication	
Identified Capabilities	Motion (A), Retain (B)	
Defined Capabilities	***Module: Klocke A***	1.2.2.3.1.1.3.2.2
	Module: Klocke B	3.2.1.1.3.1.1.3.2.2

Precision Instruments Hexapod

The Precision Instruments M840 Hexapod (PI Hex) is a motion stage. It is built from six actuators that are angled and located between two surfaces: the lower surface is fixed whilst motion is induced in the upper surface. The device is shown in the image in Figure 13-6. The PI Hex is summarised in Table 13-2.

Table 13-2: Summary of the Precision Instruments M840 Hexapod module

Equipment	The Precision Instruments M840 Hexapod	
Functionality	Motion system	
Integration Issues	None	
Identified Capabilities	Motion (A)	
Defined Capabilities	***Module: PI Hex A***	1.3.1.3.2.1.3.2.2

Kuka KRsixx 650 Robot

The Kuka KR sixx 650 robot (KR6) is a 6DoF anthropomorphic robot. It is a small industrial robot and part of a widely used range. The robot is shown in Figure 13-7 and is summarised in Table 13-3.

Table 13-3: Summary of the Kuka KRsixx robot

Equipment	The Kuka KR sixx 650 robot	
Functionality	Robotic motion system	
Integration Issues	None	
Identified Capabilities	Motion (A)	
Defined Capabilities	***Module: KR6 A***	1.3.3.1.3.3.1.2.1

Sonics and Materials ElectroPress Ultrasonic Welder

The Sonics & Materials' 40 kHz ElectroPress (EP USW), which is shown in Figure 13-8, is highly precise and controllable, both in terms of the motion of the press and the welding process itself. The EP USW is summarised in Table 13-4.

Table 13-4: Summary of the Sonics and Materials ElectroPress USW module

Equipment	The Sonics and Materials ElectroPress USW	
Functionality	Plastic welding system	
Integration Issues	Limited access to working area, Lack of standard external I/O communication,	
Identified Capabilities	Join (A)	
Defined Capabilities	***Module: EP USW A***	4.2.2.3.3.2.2.2.2.1

The USW process provides an example of the need for careful capability identification: the horn (the USW process is described in Appendix E) is moved by a linear actuator and so potentially could be mis-identified as a motion capability. Provided that the process described in 4.3.1.1 is followed, this should not happen.

There are a number of common integration issues, such as correct locating within the bay, successfully mounting the controller units and as well as the control programming aspects that are specific to the particular framework evaluated.

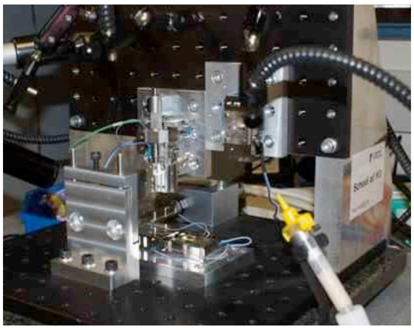


Figure 13-5: Image of the Klocke Nanotechnik system

Figure 13-6: Image of the M840 PI Hexapod

Figure 13-7: Image of the Kuka KR sixx 650 robot

Figure 13-8: Image of the Sonics and Materials Electro Press

13.1.1.4 Integration Methodology for the 3D-M Project

Figure 13-9 outlines the approach to be adopted to implement the demonstrator platform for the 3D-M project. The first phase is to specify the processes, which will be backed-up by visits to the development sites as necessary. This will be accomplished by:

1. Presentation of requirements for equipment to be integrated into the platform in this document.
2. Collation of the requirements of each process, supplied by the developer.
3. Analysis of requirements and identification of integrateable processes. (supported by site visits as needed).
4. Identification of the three system layouts.

During this phase, all of the available processes will be investigated and considered. Ideally, all of the developments will be included within the platform, but the processes that it is possible to integrate will be identified. For those processes it is not possible to directly integrate, the possibility to "virtually integrate" will be investigated. Once the three layouts are identified, the next phase will be to complete the detailed design of the three system configurations.

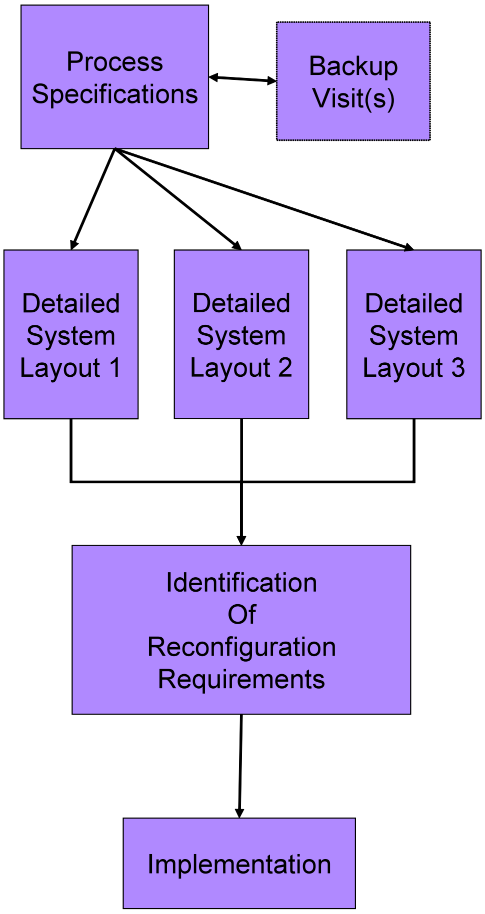


Figure 13-9: The Process Integration Methodology for the 3D-M project

The next phase will be to identify the gaps and overlaps between the three configurations and thus determine the specific requirements for reconfiguration. This will enable the system to produce all of the products will minimal time and effort between them. (The aim will be for one, highly-integrated system to be able to produce all three products – the feasibility of this has yet to be fully investigated). Finally, the system will be implemented. This will require substantial organisational effort as it is expected that all of the developers will need access to the platform to calibrate the processes.

14 Appendix D: Details of the MSA SW Tool

In all cases, the “Save” and “Exit” buttons are not explained as they perform the same function throughout.

HOME>PROJECT ADMINISTRATION

The Project is given a name and an Administrator. The Admin is likely to be the System Integrator, but this does not have to be the case. Importantly, the Admin will decide who (i.e. person) will take on each Stakeholder role. This is done in the next step.

HOME>REQUIREMENTS DEFINITION>TEAM DEFINITION

Enter the names of the Customer, Product Designer and Manufacturer for the Project. These maybe all the same person or all different. This will work like the contacts look-up in email and thus allocate that contact to that role. This is important for the proposed collaborative development concept as each contact is automatically emailed and given restricted access to the aspects of the requirements definition process relevant to their role.

It is assumed that the System Integrator is the one using the software (and thus the Admin). However, if this is not the case, details can be added as for the previous roles. NOTE: if any of the first four boxes are left blank, they are by default the responsibility of the Admin.

Additionally, one or more Sub-system Integrators and Equipment Suppliers may be selected. This is not important for the first phases of analysis but may become involved during the procurement phases (should the project been taken forwards to realisation). In most cases these will be left blank and thus by default remain the responsibility of the System Integrator.

HOME>REQUIREMENTS DEFINITION>TEAM DEFINITION>Add Contact

There is also the facility to jump to the Address book and add a contact, should they not already be listed.

HOME>REQUIREMENTS DEFINITION>PROJECT DEFINITION

The primary requirements of the Project are encompassed within the Production Scenario concept. Thus the user need only to select i) the number of Products and ii) the Production Scenario.

HOME>REQUIREMENTS DEFINITION>PROJECT DEFINITION>Create/Edit Production Scenario

Should none of the available Production Scenarios match the needs of the user, the facility is available to Edit existing files or to create new ones. This links through the form to the database table itself.

HOME>REQUIREMENTS DEFINITION>PRODUCT DEFINITION

In order to identify which products are included in the Project, it is necessary to select the Product from the drop-down list. As the Project Definition is accessed through the Project Designer Stakeholder's account, the software has access to two Product listings to select from: the Stakeholder's private/company lists and any global products placed on the system.

HOME>REQUIREMENTS DEFINITION>PRODUCT DEFINITION>Create/Edit Product

Should the required Product not exist in the listing, a new one can be created (or an exiting record altered). This is done through a form which is connected to the Product Library. The first step of this is to define each of the components. As with the Products, this is done via selection from the drop-down list which presents all options available to the user. Additional components can be created if needed (see below).

The final step is to ensure the connections are fully defined between the components (see below).

HOME>REQUIREMENTS DEFINITION>PRODUCT DEFINITION>Create/Edit Product>Create/Edit Component

If the correct component is not available, one can be defined. The form which opens is connected to the Component library and is linked to the Capability Taxonomy as the selections made at this point will affect the Capability Definition later in the process.

HOME>REQUIREMENTS DEFINITION>PRODUCT DEFINITION>Create/Edit Product>Define Connections

In addition, it is necessary to define the connections between the components. In this form, first the relevant connection is selected from the drop-down list. Then this is defined based upon the “Join” section of the Capability Taxonomy, again via a series of drop-down lists.

HOME>REQUIREMENTS DEFINITION>SYSTEM DEFINITION

The next phase is to define the existing manufacturing system. The first step is to select the number of modules, then go to the drop-down lists for each module number and select the type/model of module. This list is linked to the available Module libraries. Again, this will be limited to the user’s private list and any globally listed modules.

HOME>REQUIREMENTS DEFINITION>SYSTEM DEFINITION>Create/Edit Module

Should the relevant module not be available then this facility enables a new module listing to be created or adapted from an existing record. This is again linked to the Taxonomy and the drop-down lists change depending upon the previous selection. However, this is based upon the assumption that the user has a sufficiently detailed understanding of both the module and the Taxonomy to provide the definition. Should this not be the case, a tool is created to assist in the definition.

HOME>REQUIREMENTS DEFINITION>SYSTEM DEFINITION>Create/Edit Module>Module Specification Tool

The tool is similarly linked as above, however it uses a series of questions; the answers to which can be determined by observation of the module and will specify it with respect to the Taxonomy.

HOME>CAPABILITY EVALUATION>CAPABILITY IDENTIFICATION

With the requirements derived, the next phase of the system is to analyse the Project at the capability level. The first element of this is to identify all of the capabilities required to deliver each product. Thus at the Capability Identification page, the relevant product is selected from the drop-down list. The text will then indicate whether or not the capabilities for that product have been identified or not.

HOME>CAPABILITY EVALUATION>CAPABILITY IDENTIFICATION>Capability Identification Tool

In order to identify the required capabilities for a product, the MS Access software is linked to an external tool. This tool comprises a template and a rule set. The template aids in the creation of a standardised Process Flow Diagram (PFD) showing the main processes that delivery the product. Once created, the rule set is applied in order to identify the location and sequence of the capabilities. Any of these capabilities can be set to zero later in the definition process.

HOME>CAPABILITY EVALUATION>CAPABILITY DEFINITION

With all of the capabilities identified, the next phase is to define each of them. Most of the definition comes from the requirements elicited earlier in the process. However, each capability can be viewed by selecting from the two drop-down lists and clicking “View”.

HOME>CAPABILITY EVALUATION>CAPABILITY DEFINITION>Define

The definition tool is linked to the capability taxonomy and a series of questions will define the capability.

HOME>CAPABILITY EVALUATION>CAPABILITY COMPARISON

With all Capabilities defined the next phase is to compare the required and available capability sets. This page displays an overview of the system and products that will be compared, thus if needed the user can go back and add or remove products or modules. There is a button to perform the comparison.

HOME>CAPABILITY EVALUATION>CAPABILITY COMPARISON>Comparison Matrix

When clicking through from the previous form, the system automatically performs the comparison using the Comparison Matrix Tool. The results are displayed along with guidelines for their use/meaning.

HOME>CAPABILITY EVALUATION>CAPABILITY SET ANALYSIS

After the comparison process, it may be desirable to view the configuration options for individual products and to alter it to suit a particular need… It is also an opportunity to refine the configurations through the capabilities.

HOME>CONFIGURATION PLANNING>PRODUCTION SEQUENCING

If a defined production sequence is already known, then that data can be entered and saved at this stage in order to later delivery the system lifecycle and plan. However, if the sequence is only partially known or completely unknown/unspecified then the Production Sequencing Tool can enable the most efficient sequence to be determined.

HOME>CONFIGURATION PLANNING>PRODUCTION SEQUENCING>Sequencing Tool

The Production Sequencing Tool utilises the previously used comparison matrix to establish a Similarity Coefficient between all of the products and the existing system to find the order of production that will minimise the reconfiguration effort. Regardless of the overall strategy behind each configuration, this is a singularly desirable result.

Note: the sequence can be found by either a) focussing on the ideal sequence for the products, then picking the best fit to the system from the two available or b) including the system similarity coefficient from the start and only including it once, thus finding the ideal sequence straight off.

Note: the Compare Products button will not be needed in the final SW.

HOME>CONFIGURATION PLANNING>EQUIPMENT ALLOCATION

With the configurations determined in terms of the capability sets, the next step is to allocate equipment in accordance with the priorities set.

HOME>CONFIGURATION PLANNING>EQUIPMENT ALLOCATION>Equipment Pool

By running this form, the complex module-equipment allocation is performed based upon the Production Scenario selected. The total pool of equipment is displayed. In addition, the user can perform a “quick change” of the scenario to see the effects.

Note: this is all linked to the separate and complex equipment allocation calculations.

HOME>CONFIGURATION PLANNING>EQUIPMENT ALLOCATION>Equipment Pool> View Configuration

It is also possible to view individual equipment configurations, this is envisaged in order to accommodate the possible need to look at one high-priority configuration.

Note: the issue of line balancing is not directly considered here.

HOME>CONFIGURATION PLANNING>SYSTEM LIFECYCLE

The final steps in the methodology are to project the impacts and requirements of implementing the derived system.

HOME>CONFIGURATION PLANNING>SYSTEM LIFECYCLE>View Projected Lifecycle

This form displays the projected lifecycle of the system chronologically. It highlights the modules to be removed and to be added at each configuration and also confirms the configuration required for each product.

HOME>CONFIGURATION PLANNING>SYSTEM LIFECYCLE>View Projected Performance / Costings

These forms display a number of performance graphs for the system and also key indicators such as capital cost.

Note: the costing and performance calculations require that both Equipment Suppliers and the System Integrator include a number of cost factors into the system (i.e. module cost, installation time etc.)

HOME>CONFIGURATION PLANNING>SYSTEM LIFECYCLE>Export to…

Finally, these buttons implement Macros to export important data to external management tools to facilitate the physical realisation of the system.

15 Appendix E: Full Evidence for Test Case 1

Table 15-1: Summary of the five Capability Sets for Test Case 1

Set A		Set B	
Cap Locator	**Cap Definition**	**Cap Locator**	**Cap Definition**
PFA001	2,2,4,2,3	PFB001	2,2,1,1,1
PFA001	3,1,4,2,3	PFB001	3,1,1,1,1
PFA001-PFA002	1,1,7,2,2	PFB001-PFB002	1,1,39,2,2
PFA002	4,1,2,2,2	PFB002	4,1,2,2,1
PFA002	3,2,4,2,3	PFB002	3,2,1,1,1
PFA002 -	1,2,-	PFB002 -	1,2,-
PFA003	2,2,4,2,3	PFB003	2,2,2,1,1
PFA003	3,1,4,2,3	PFB003	3,1,2,1,1
PFA003 -	1,1,7,2,2	PFB003 -	1,1,39,2,2
PFA004	4,2,1,2,2	PFB004	4,1,2,2,5
PFA004	-	PFB004	-
PFA004 - OUT	1,2,-	PFB004 - OUT	1,2,-

Set C		Set D	
Cap Locator	**Cap Definition**	**Cap Locator**	**Cap Definition**
PFC001	2,2,1,3,3	PFD001	2,3,4,1,1
PFC001	3,1,1,3,3	PFD001	3,1,4,1,1
PFC001-PFC002	1,1,39,1,2	PFD001-PFD002	1,1,31,3,2
PFC002	4,1,2,1,2	PFD002	4,1,2,3,2
PFC002	3,2,1,3,3	PFD002	3,2,4,1,1
PFC002 - PFC004	1,2,-	PFD002 -	1,2,-
PFC003	2,3,4,3,3	PFD003	2,3,5,1,1
PFC003	3,1,4,3,3	PFD003	3,1,5,1,1
PFC003 - PFC004	1,1,31,1,2	PFD003 -	1,1,7,3,2
PFC004	4,2,3,1,1	PFD004	4,2,1,3,1
PFC004	-	PFD004	-
PFC004 - OUT	1,2,-	PFD004 - OUT	1,2,-

Set E	
Cap Locator	**Cap Definition**
PFE001	2,2,2,2,2
PFE001	3,1,2,2,2
PFE001-PFE002	1,1,7,2,2
PFE002	4,1,2,2,4
PFE002	3,2,2,2,2
PFE002 - PFE004	1,2,-
PFE003	2,2,2,2,2
PFE003	3,1,2,2,2
PFE003 - PFE004	1,1,7,2,2
PFE004	4,1,2,2,4
PFE004	-
PFE004 - OUT	1,2,-

Table 15-2 shows the definitions for the Existing Capabilities, whilst Table 15-3 to Table 15-7 show the definitions for the Required Capabilities.

Table 15-2: Definition of the Existing Capabilities for Test Case 1

Cap Locator	Cap Designator	Cap Definition
C_{EXA}	C_{EXA}01	1,1,39,2,2,3
C_{EXC}	C_{EXC}01	2,3,2,2,1
C_{EXB}	C_{EXB}01	3,1,2,2,2
C_{EXD}	C_{EXD}01	3,2,2,2,3
C_{EXE}	C_{EXE}01	4,1,2,2,2

Table 15-3: Definition of the Required Capabilities for product A of Test Case 1

Cap Locator	Cap Designator	Cap Definition
PFA001-PFA002	C_{RQA} 01	1,1,7,2,2
PFA003 - PFA004	C_{RQA} 02	1,1,7,2,2
PFA002 - PFA004	C_{RQA} 03	1,2,-
PFA004 - OUT	C_{RQA} 04	1,2,-
PFA001	C_{RQA} 05	2,2,4,2,3
PFA003	C_{RQA} 06	2,2,4,2,3
PFA001	C_{RQA} 07	3,1,4,2,3
PFA003	C_{RQA} 08	3,1,4,2,3
PFA002	C_{RQA} 09	3,2,4,2,3
PFA002	C_{RQA} 10	4,1,2,2,2
PFA004	C_{RQA} 11	4,2,1,2,2

Table 15-4: Definition of the Required Capabilities for product B of Test Case 1

PFB001-PFB002	C_{RQB} 01	1,1,39,2,2
PFB003 – PFB004	C_{RQB} 02	1,1,39,2,2
PFB002 – PFB004	C_{RQB} 03	1,2,-
PFB004 – OUT	C_{RQB} 04	1,2,-
PFB001	C_{RQB} 05	2,2,1,1,1
PFB003	C_{RQB} 06	2,2,2,1,1
PFB001	C_{RQB} 07	3,1,1,1,1
PFB003	C_{RQB} 08	3,1,2,1,1
PFB002	C_{RQB} 09	3,2,1,1,1
PFB002	C_{RQB} 10	4,1,2,2,1
PFB004	C_{RQB} 11	4,1,2,2,5

Table 15-5: Definition of the Required Capabilities for product C of Test Case 1

PFC001-PFC002	C_{RQC} 01	1,1,39,1,2
PFC003 - PFC004	C_{RQC} 02	1,1,31,1,2
PFC002 - PFC004	C_{RQC} 03	1,2,-
PFC004 - OUT	C_{RQC} 04	1,2,-
PFC001	C_{RQC} 05	2,2,1,3,3
PFC003	C_{RQC} 06	2,3,4,3,3
PFC001	C_{RQC} 07	3,1,1,3,3
PFC003	C_{RQC} 08	3,1,4,3,3
PFC002	C_{RQC} 09	3,2,1,3,3
PFC002	C_{RQC} 10	4,1,2,1,2
PFC004	C_{RQC} 11	4,2,3,1,1

Table 15-6: Definition of the Required Capabilities for product D of Test Case 1

PFD001-PFD002	C_{RQD} 01	1,1,31,3,2
PFD003 – PFD004	C_{RQD} 02	1,1,7,3,2
PFD002 – PFD004	C_{RQD} 03	1,2,-
PFD004 – OUT	C_{RQD} 04	1,2,-
PFD001	C_{RQD} 05	2,3,4,1,1
PFD003	C_{RQD} 06	2,3,5,1,1
PFD001	C_{RQD} 07	3,1,4,1,1
PFD003	C_{RQD} 08	3,1,5,1,1
PFD002	C_{RQD} 09	3,2,4,1,1
PFD002	C_{RQD} 10	4,1,2,3,2
PFD004	C_{RQD} 11	4,2,1,3,1

Table 15-7: Definition of the Required Capabilities for product E of Test Case 1

PFE001-PFE002	C_{RQE} 01	1,1,7,2,2
PFE003 - PFE004	C_{RQE} 02	1,1,7,2,2
PFE002 - PFE004	C_{RQE} 03	1,2,-
PFE004 - OUT	C_{RQE} 04	1,2,-
PFE001	C_{RQE} 05	2,2,2,2,2
PFE003	C_{RQE} 06	2,2,2,2,2
PFE001	C_{RQE} 07	3,1,2,2,2
PFE003	C_{RQE} 08	3,1,2,2,2
PFE002	C_{RQE} 09	3,2,2,2,2
PFE002	C_{RQE} 10	4,1,2,2,4
PFE004	C_{RQE} 11	4,1,2,2,4

Where;

C_{RQx} = *Required Capabilities product x*

The key to the matrices shown in Table 15-9 to Table 15-13 is provided in Table 15-8.

Table 15-8: Key to the Comparison Matrix

Large Match	=	1
Small Match	=	:1
Unknown Match	=	U
No Match	=	0

Table 15-9: Comparison Matrix for Product A

		REQUIRED CAPS											
		Motion				Feed		Retain			Join		**Total C_{EXS}**
		$C_{RQA}01$	$C_{RQA}02$	$C_{RQA}03$	$C_{RQA}04$	$C_{RQA}05$	$C_{RQA}06$	$C_{RQA}07$	$C_{RQA}08$	$C_{RQA}09$	$C_{RQA}10$	$C_{RQA}11$	
EXISTING CAPS	$C_{EXA}01$	1	1	0	0	-	-	-	-	-	-	-	**2**
	$C_{EXC}01$	-	-	-	-	0	0	-	-	-	-	-	**0**
	$C_{EXB}01$	-	-	-	-	-	-	0	0	0	-	-	**0**
	$C_{EXD}01$	-	-	-	-	-	-	0	0	0	-	-	**0**
	$C_{EXE}01$	-	-	-	-	-	-	-	-	-	1	0	**1**
Total C_{REQ}		**1**	**1**	**0**	**0**	**0**	**0**	**0**	**0**	**0**	**1**	**0**	

Table 15-10: Comparison Matrix for Product B

		REQUIRED CAPS											
		Motion				Feed		Retain			Join		**Total C_{EXS}**
		$C_{RQB}01$	$C_{RQB}02$	$C_{RQB}03$	$C_{RQB}04$	$C_{RQB}05$	$C_{RQB}06$	$C_{RQB}07$	$C_{RQB}08$	$C_{RQB}09$	$C_{RQB}10$	$C_{RQB}11$	
EXISTING CAPS	$C_{EXA}01$	1	1	0	0	-	-	-	-	-	-	-	**2**
	$C_{EXC}01$	-	-	-	-	0	0	-	-	-	-	-	**0**
	$C_{EXB}01$	-	-	-	-	-	-	:1	1	0	-	-	**1:1**
	$C_{EXD}01$	-	-	-	-	-	-	0	0	:1	-	-	**:1**
	$C_{EXE}01$	-	-	-	-	-	-	-	-	-	:1	:1	**:2**
Total C_{REQ}		**1**	**1**	**0**	**0**	**0**	**0**	**:1**	**1**	**:1**	**:1**	**:1**	

Table 15-11: Comparison Matrix for Product C

		REQUIRED CAPS											
		Motion				Feed		Retain			Join		**Total C_{EXS}**
		$C_{RQC}01$	$C_{RQC}02$	$C_{RQC}03$	$C_{RQC}04$	$C_{RQC}05$	$C_{RQC}06$	$C_{RQC}07$	$C_{RQC}08$	$C_{RQC}09$	$C_{RQC}10$	$C_{RQC}11$	
EXISTING CAPS	$C_{EXA}01$	1	0	0	0	-	-	-	-	-	-	-	**1**
	$C_{EXC}01$	-	-	-	-	0	0	-	-	-	-	-	**0**
	$C_{EXB}01$	-	-	-	-	-	-	:1	0	0	-	-	**:1**
	$C_{EXD}01$	-	-	-	-	-	-	0	0	:1	-	-	**:1**
	$C_{EXE}01$	-	-	-	-	-	-	-	-	-	0	0	**0**
Total C_{REQ}		**1**	**0**	**0**	**0**	**0**	**0**	**:1**	**0**	**:1**	**0**	**0**	

Table 15-12: Comparison Matrix for Product D

		REQUIRED CAPS											
		Motion				Feed		Retain			Join		**Total C_{EXS}**
		$C_{RQD}01$	$C_{RQD}02$	$C_{RQD}03$	$C_{RQD}04$	$C_{RQD}05$	$C_{RQD}06$	$C_{RQD}07$	$C_{RQD}08$	$C_{RQD}09$	$C_{RQD}10$	$C_{RQD}11$	
EXISTING CAPS	$C_{EXA}01$	0	0	0	0	-	-	-	-	-	-	-	**0**
	$C_{EXC}01$	-	-	-	-	0	0	-	-	-	-	-	**0**
	$C_{EXB}01$	-	-	-	-	-	-	0	0	0	-	-	**0**
	$C_{EXD}01$	-	-	-	-	-	-	0	0	0	-	-	**0**
	$C_{EXE}01$	-	-	-	-	-	-	-	-	-	0	0	**0**
Total C_{REQ}		**0**	**0**	**0**	**0**	**0**	**0**	**0**	**0**	**0**	**0**	**0**	

Table 15-13: Comparison Matrix for Product E

		REQUIRED CAPS											
		Motion				Feed		Retain			Join		**Total C_{EXS}**
		$C_{RQE}01$	$C_{RQE}02$	$C_{RQE}03$	$C_{RQE}04$	$C_{RQE}05$	$C_{RQE}06$	$C_{RQE}07$	$C_{RQE}08$	$C_{RQE}09$	$C_{RQE}10$	$C_{RQE}11$	
EXISTING CAPS	$C_{EXA}01$	1	1	0	0	-	-	-	-	-	-	-	**2**
	$C_{EXC}01$	-	-	-	-	0	0	-	-	-	-	-	**0**
	$C_{EXB}01$	-	-	-	-	-	-	1	1	0	-	-	**2**
	$C_{EXD}01$	-	-	-	-	-	-	0	0	1	-	-	**1**
	$C_{EXE}01$	-	-	-	-	-	-	-	-	-	:1	:1	**:2**
Total C_{REQ}		**1**	**1**	**0**	**0**	**0**	**0**	**1**	**1**	**1**	**:1**	**:1**	

Having completed the comparison matrices, it can be determined whether or not a module meets each required Capability. If not, then an identifier is used to indicate the need to procure a module. This is summarised in Table 15-14.

After the Capabilities to be procured have been assigned relevant and appropriate modules, it is then possible to generate the outline configurations, as summarised in Table 15-15, which provides a capability-based list whereby there are some repeats. This is resolved by the final table (Table 15-16) which lists the modules and their type for each configuration.

Table 15-14: Summary of the satisfaction of the Required Capabilities for Test Case 1

Set A		Set B	
Required Cap's	**Equip. Cap's**	**Required Cap's**	**Equip. Cap's**
C_{RQA} 01	C_{EXA}	C_{RQB} 01	C_{EXA}
C_{RQA} 02	C_{EXA}	C_{RQB} 02	C_{EXA}
C_{RQA} 03	C_{PR01}	C_{RQB} 03	C_{PR09}
C_{RQA} 04	C_{PR02}	C_{RQB} 04	C_{PR10}
C_{RQA} 05	C_{PR03}	C_{RQB} 05	C_{PR11}
C_{RQA} 06	C_{PR04}	C_{RQB} 06	C_{PR12}
C_{RQA} 07	C_{PR05}	C_{RQB} 07	C_{EXC}
C_{RQA} 08	C_{PR06}	C_{RQB} 08	C_{EXC}
C_{RQA} 09	C_{PR07}	C_{RQB} 09	C_{EXD}
C_{RQA} 10	C_{EXE}	C_{RQB} 10	C_{EXE}
C_{RQA} 11	C_{PR08}	C_{RQB} 11	C_{EXE}
Set C		**Set D**	
Required Cap's	**Equip. Cap's**	**Required Cap's**	**Equip. Cap's**
C_{RQC} 01	C_{EXA}	C_{RQD} 01	C_{PR21}
C_{RQC} 02	C_{PR13}	C_{RQD} 02	C_{PR22}
C_{RQC} 03	C_{PR14}	C_{RQD} 03	C_{PR23}
C_{RQC} 04	C_{PR15}	C_{RQD} 04	C_{PR24}
C_{RQC} 05	C_{PR16}	C_{RQD} 05	C_{PR25}
C_{RQC} 06	C_{PR17}	C_{RQD} 06	C_{PR26}
C_{RQC} 07	C_{EXC}	C_{RQD} 07	C_{PR27}
C_{RQC} 08	C_{PR18}	C_{RQD} 08	C_{PR28}
C_{RQC} 09	C_{EXD}	C_{RQD} 09	C_{PR29}
C_{RQC} 10	C_{PR19}	C_{RQD} 10	C_{PR30}
C_{RQC} 11	C_{PR20}	C_{RQD} 11	C_{PR31}
Set E			
Required Cap's	**Equip. Cap's**		
C_{RQE} 01	C_{EXA}		
C_{RQE} 02	C_{EXA}		
C_{RQE} 03	C_{PR32}		
C_{RQE} 04	C_{PR33}		
C_{RQE} 05	C_{PR34}		
C_{RQE} 06	C_{PR35}		
C_{RQE} 07	C_{EXC}		
C_{RQE} 08	C_{EXC}		
C_{RQE} 09	C_{EXD}		
C_{RQE} 10	C_{EXE}		
C_{RQE} 11	C_{EXE}		

Table 15-15: Summary of the configurations and the modules for Test Case 1

Set A		Set B	
Required Cap’s	**Equip. Cap’s**	**Required Cap’s**	**Equip. Cap’s**
C_{RQA} 01	C_{EXA}	C_{RQB} 01	C_{EXA}
C_{RQA} 02	C_{EXA}	C_{RQB} 02	C_{EXA}
C_{RQA} 03	N/A	C_{RQB} 03	N/A
C_{RQA} 04	N/A	C_{RQB} 04	N/A
C_{RQA} 05	C_{MODF}	C_{RQB} 05	C_{MODG}
C_{RQA} 06	C_{MODF}	C_{RQB} 06	C_{MODH}
C_{RQA} 07	C_{MODO}	C_{RQB} 07	C_{EXB}
C_{RQA} 08	C_{MODO}	C_{RQB} 08	C_{EXB}
C_{RQA} 09	C_{MODP}	C_{RQB} 09	C_{EXD}
C_{RQA} 10	C_{EXE}	C_{RQB} 10	C_{EXE}
C_{RQA} 11	C_{MODR}	C_{RQB} 11	C_{EXE}

Set C		Set D	
Required Cap’s	**Equip. Cap’s**	**Required Cap’s**	**Equip. Cap’s**
C_{RQC} 01	C_{EXA}	C_{RQD} 01	C_{MODS}
C_{RQC} 02	C_{EXA}	C_{RQD} 02	C_{MODS}
C_{RQC} 03	N/A	C_{RQD} 03	N/A
C_{RQC} 04	N/A	C_{RQD} 04	N/A
C_{RQC} 05	C_{MODJ}	C_{RQD} 05	C_{MODL}
C_{RQC} 06	C_{MODK}	C_{RQD} 06	C_{MODM}
C_{RQC} 07	C_{EXB}	C_{RQD} 07	C_{MODO}
C_{RQC} 08	C_{MODO}	C_{RQD} 08	C_{MODQ}
C_{RQC} 09	C_{EXD}	C_{RQD} 09	C_{MODP}
C_{RQC} 10	C_{EXE}	C_{RQD} 10	C_{EXE}
C_{RQC} 11	C_{MODR}	C_{RQD} 11	C_{MODR}

Set E	
Required Cap’s	**Equip. Cap’s**
C_{RQE} 01	C_{EXA}
C_{RQE} 02	C_{EXA}
C_{RQE} 03	N/A
C_{RQE} 04	N/A
C_{RQE} 05	C_{MODN}
C_{RQE} 06	C_{MODN}
C_{RQE} 07	C_{EXB}
C_{RQE} 08	C_{EXB}
C_{RQE} 09	C_{EXD}
C_{RQE} 10	C_{EXE}
C_{RQE} 11	C_{EXE}

Table 15-16: Summary of the module types and specific module used for each configuration

Configuration A		**Configuration B**	
Module Type	**Module Ref**	**Module Type**	**Module Ref**
Motion	EX A	Motion	EX A
Feed	MOD F	Feed	MOD G
Retain	MOD O	Feed	MOD H
Retain	MOD P	Retain	EX B
Join	EX E	Retain	EX D
Join	MOD R	Join	EX E
Configuration C		**Configuration D**	
Module Type	**Module Ref**	**Module Type**	**Module Ref**
Motion	EX A	Motion	MOD S
Motion	MOD S	Feed	MOD L
Feed	MOD J	Feed	MOD M
Feed	MOD K	Retain	MOD O
Retain	EX B	Retain	MOD Q
Retain	MOD O	Retain	MOD P
Retain	EX D	Join	EX E
Join	EX E	Join	MOD R
Join	MOD R		
Configuration E			
Module Type	**Module Ref**		
Motion	EX A		
Feed	MOD N		
Retain	EX B		
Retain	EX D		
Join	EX E		

16 Appendix F: Full Evidence for Test Case 2

16.1 Introduction

The main purpose of Test Case 2 is to demonstrate the elements of the approach that are significantly affected by the implementation of a more substantial application. The Test Case utilises more complex products that are derived from the 3D-M project as well as from other research activities.

The aspects of the approach most under consideration are within the Capability Model, specifically the Required Capabilities identification, definition and comparison. Test Case 1 used five products each with only two components. Whilst this test case is highly suitable for a relatively concise demonstration of the entire approach, it is not truly representative of microdevices. Therefore, any issues specifically associated with the volume of data and likely results from representative microdevices cannot be identified without the consideration of accurate microdevices.

Furthermore, one of the primary issues identified in Test Case 1 was the volume of data to be entered into the system. Therefore, a revised definition procedure is considered.

16.1.1 Test Case 2 Situation

Test Case 2 is built upon the scenario described in Section 3.5.2. In this situation, Company X has developed six different products that are all due to be clinically trialled prior to their approval for sale and mass production. All of the products are required only in small batches and so the priorities for the customer are to minimise reconfiguration effort and cost.

16.1.2 Existing System Specification

The existing (and available) equipment consists of the following:

1 x SCARA robot with auto tool changer	*ModA*
1 x 2 axis liner robotic stage with manual tool changer	*ModB*
1 x mechanical gripper, 3 fingered for cylindrical parts	*ModC*
1 x mechanical gripper, 4 fingered for cubic parts	*ModD*
1 x bowl feeder for cylindrical parts	*ModE*

• 1 x tray feeder for cubic parts	*ModF*
• 1 x 6-station conveyor unit	*ModG*

16.1.3 Product Specifications

The products are defined according to their constituent parts and the relationships between them – the liaisons. These are used to define the capabilities required in order to realise the assembly of the product. The six products considered are:

1. Camera Pill
2. Dispensing Pill
3. Diagnostics Pill
4. Fluid Separator
5. Micro Pump
6. Acoustic Amplifier

The following sub-sections describe each product in greater detail.

16.1.3.1 Camera Pill

Consists of: Body, Coil, Battery, PCB, Camera, Lens.

- The Battery and Camera dock onto either side of the PCB.
- The Coil has a push-fit into the Body.
- The PCB S-A fits inside the Coil, connections are made "automatically".
- The Lens fits onto the Body, the joint must be sealed. The joint also retains the PCB S-A into place.

16.1.3.2 Dispensing Pill

Consists of: Body, Coil, Battery, PCB, SMA Actuator, Plunger, Stopper.

- The pill is supplied to customer (a pharmaceutical) without the drug and the Stoppers separately.
- The Plunger is to be joined to the SMA Actuator.
- The Battery and SMA Actuator dock onto either side of the PCB.

- The Coil has a push-fit into the Body, connections are made “automatically”.
- The PCB S-A fits inside the Coil.

16.1.3.3 Diagnostics Pill

Consists of: Body, Coil, Battery, PCB, Membrane, Sensors, Cap.

- The Cap is dissolved away in the stomach, exposing the sensors, but the Membrane protects the rest of the internals of the pill.
- The Battery docks onto one side of the PCB.
- The Sensors dock onto the other side of the PCB, through the Membrane.
- The Coil has a push-fit into the Body.
- The PCB S-A fits inside the Coil, connections are made “automatically”.
- The Membrane has an interference fit to the Body.
- The Cap fits onto the Body with an interference fit.

16.1.3.4 Fluidic Separator

Consists of: Body, Feature Block (3 off) and Cap

- The Body is cylindrical and contains the three Feature Blocks.
- The Feature Blocks have no rotational alignment and are placed inside the body.
- The Cap is used to compress the Feature Blocks together and to provide the seal.

16.1.3.5 Micro Pump

Consists of: Body with Coil, Magnet, Magnet Case, Pump Shaft and Port.

- The Body is manufactured with an internal coil to drive the Magnet.
- The Magnet Case is inserted into the Body but remains able to spin inside it.
- The Magnet is inserted in and joined to the Magnet Case.
- The Pump Shaft is inserted in and joined to the Magnet.

- The Port is joined to the Body to provide support and location for the moving parts.

16.1.3.6 Acoustic Amplifier

Consists of: Body, Plate Seat, Plate, Large Membrane, Small Membrane, Large Clip and Small Clip.

- The Body contains the Plate assembly and has a Membrane and Clip on each end.
- The Plate Seat is inserted into the Body and joined to it.
- The Plate clips to the Plate Seat.
- The Membranes are joined to their respective ends of the Body.
- The Clips retain their respective Membranes.

16.1.4 Consideration of Liaisons

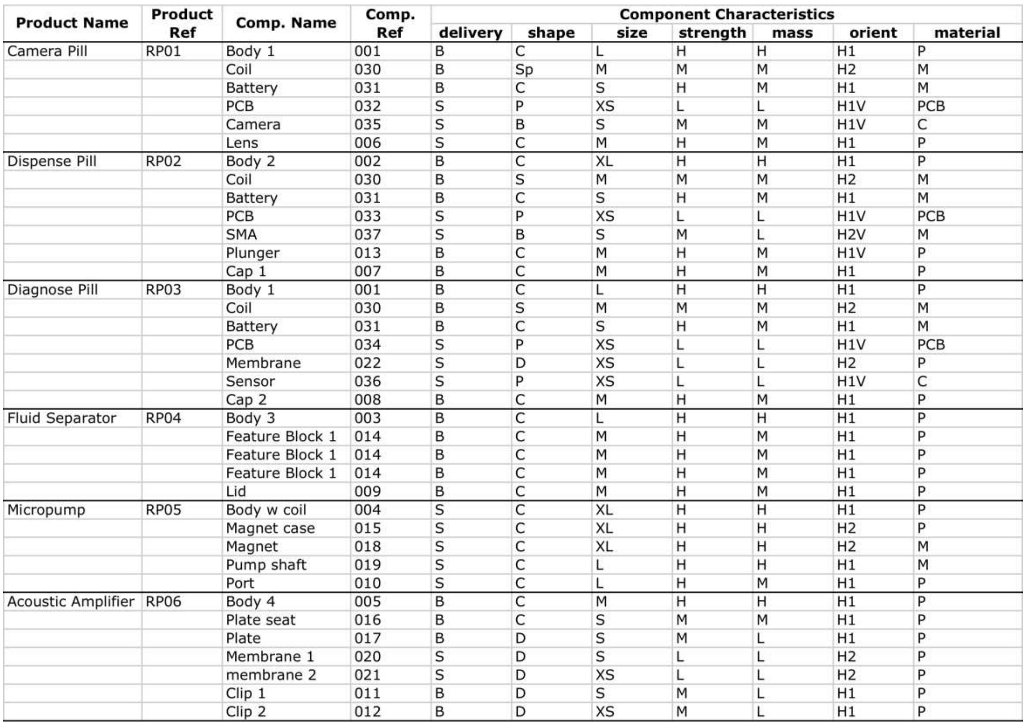
The analysis of Test Case 2 considers a different approach in the specification and definition of both the required products and available system; *Liaisons*. *Equipment Liaisons* are the connections between equipment modules and between the modules and the system framework. *Product Liaisons* are the connections between components within a product.

Equipment Liaisons are important in the Capability Identification and in the final realisation of a system. During Capability Identification, Equipment Liaisons can be used to identify Emergent Capabilities. During final realisation, the liaisons enable the System Integrator to plan the details of the integration of the modules.

Product Liaisons are a potential route for the identification and definition of the Required Capabilities. The Product Designer can define each component part within a product using the appropriate taxonomy. They can then identify all of the liaisons between components in that product and define them, again using the taxonomy. Then, the Product Designer must only identify the sequence in which components are brought in for the assembly sequence to be identified. Furthermore, the application of a few key rules enables the definitions made to support the definition of the capabilities without additional effort.

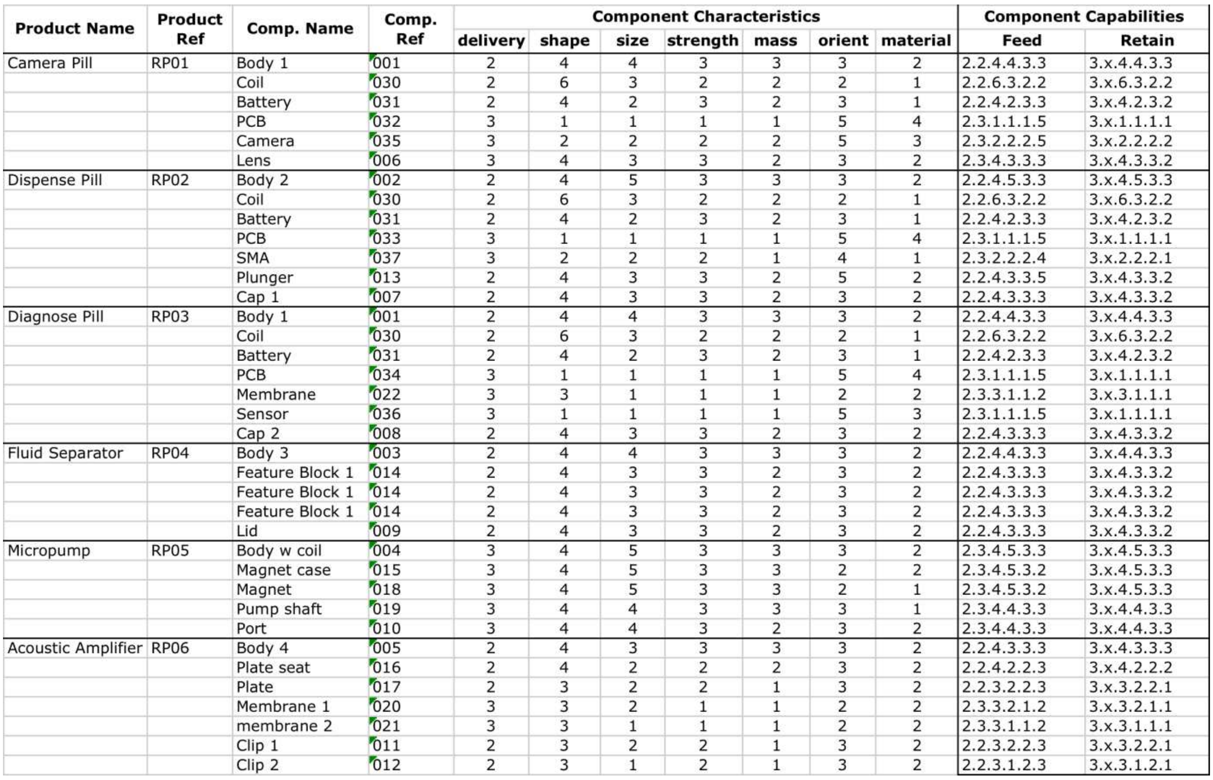
16.1.5 Product Liaison and Component Definition

Definition of the product components and their liaisons is made in a tabulated format, shown in Figures 16-1 to 16-3.



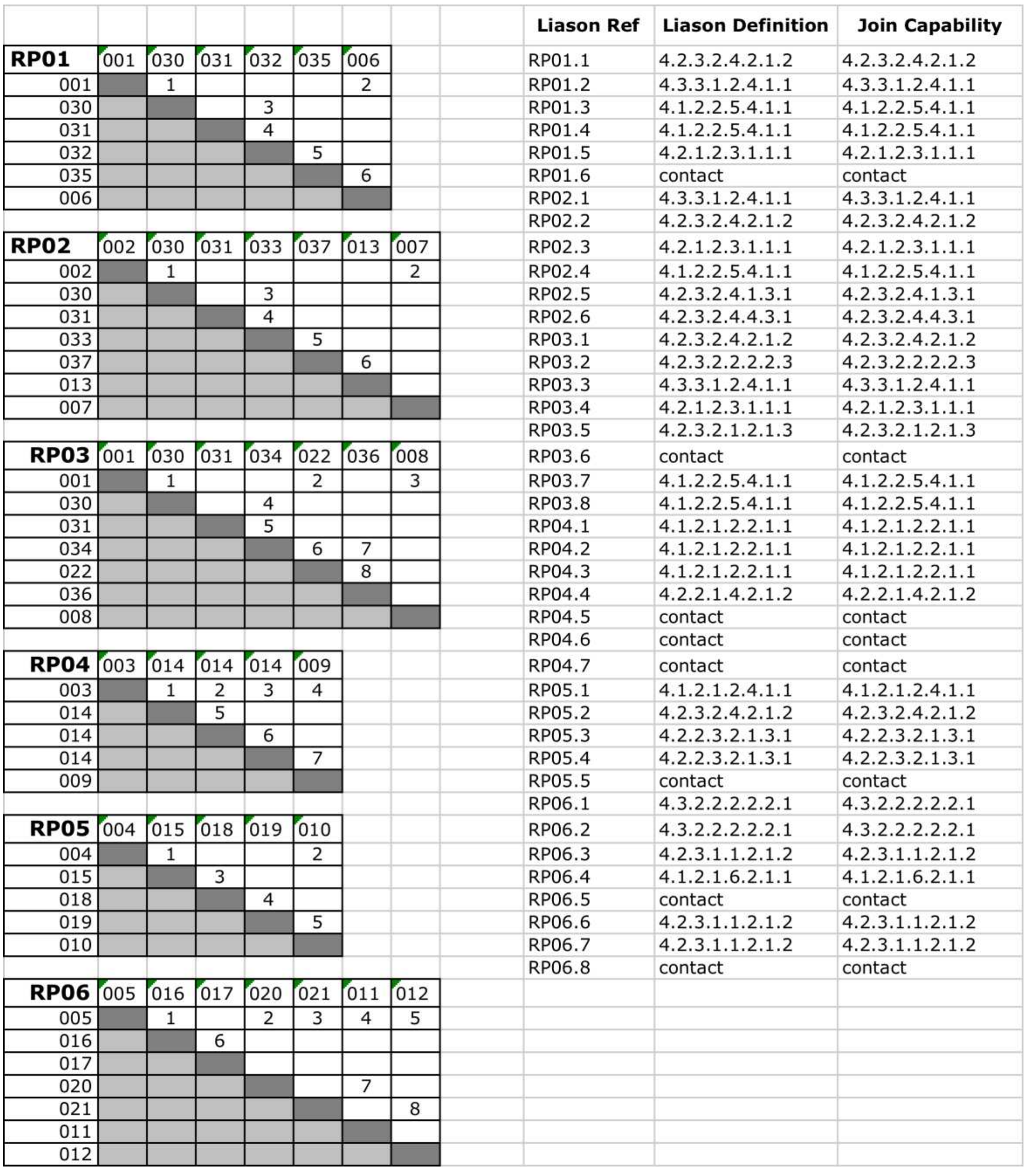
Product Name	Product Ref	Comp. Name	Comp. Ref	Component Characteristics						
				delivery	shape	size	strength	mass	orient	material
Camera Pill	RP01	Body 1	001	B	C	L	H	H	H1	P
		Coil	030	B	Sp	M	M	M	H2	M
		Battery	031	B	C	S	H	M	H1	M
		PCB	032	S	P	XS	L	L	H1V	PCB
		Camera	035	S	B	S	M	M	H1V	C
		Lens	006	S	C	M	H	M	H1	P
Dispense Pill	RP02	Body 2	002	B	C	XL	H	H	H1	P
		Coil	030	B	S	M	M	M	H2	M
		Battery	031	B	C	S	H	M	H1	M
		PCB	033	S	P	XS	L	L	H1V	PCB
		SMA	037	S	B	S	M	L	H2V	M
		Plunger	013	B	C	M	H	M	H1V	P
		Cap 1	007	B	C	M	H	M	H1	P
Diagnose Pill	RP03	Body 1	001	B	C	L	H	H	H1	P
		Coil	030	B	S	M	M	M	H2	M
		Battery	031	B	C	S	H	M	H1	M
		PCB	034	S	P	XS	L	L	H1V	PCB
		Membrane	022	S	D	XS	L	L	H2	P
		Sensor	036	S	P	XS	L	L	H1V	C
		Cap 2	008	B	C	M	H	M	H1	P
Fluid Separator	RP04	Body 3	003	B	C	L	H	H	H1	P
		Feature Block 1	014	B	C	M	H	M	H1	P
		Feature Block 1	014	B	C	M	H	M	H1	P
		Feature Block 1	014	B	C	M	H	M	H1	P
		Lid	009	B	C	M	H	M	H1	P
Micropump	RP05	Body w coil	004	S	C	XL	H	H	H1	P
		Magnet case	015	S	C	XL	H	H	H2	P
		Magnet	018	S	C	XL	H	H	H2	M
		Pump shaft	019	S	C	L	H	H	H1	M
		Port	010	S	C	L	H	M	H1	P
Acoustic Amplifier	RP06	Body 4	005	B	C	M	H	H	H1	P
		Plate seat	016	B	C	S	M	M	H1	P
		Plate	017	B	D	S	M	L	H1	P
		Membrane 1	020	S	D	S	L	L	H2	P
		membrane 2	021	S	D	XS	L	L	H2	P
		Clip 1	011	B	D	S	M	L	H1	P
		Clip 2	012	B	D	XS	M	L	H1	P

Figure 16-1: Definition of Component characteristics



Product Name	Product Ref	Comp. Name	Comp. Ref	Component Characteristics							Component Capabilities	
				delivery	shape	size	strength	mass	orient	material	Feed	Retain
Camera Pill	RP01	Body 1	001	2	4	4	3	3	3	2	2.2.4.4.3.3	3.x.4.4.3.3
		Coil	030	2	6	3	2	2	2	1	2.2.6.3.2.2	3.x.6.3.2.2
		Battery	031	2	4	2	3	2	3	1	2.2.4.2.3.3	3.x.4.2.3.2
		PCB	032	3	1	1	1	1	5	4	2.3.1.1.1.5	3.x.1.1.1.1
		Camera	035	3	2	2	2	2	5	3	2.3.2.2.2.5	3.x.2.2.2.2
		Lens	006	3	4	3	3	2	3	2	2.3.4.3.3.3	3.x.4.3.3.2
Dispense Pill	RP02	Body 2	002	2	4	5	3	3	3	2	2.2.4.5.3.3	3.x.4.5.3.3
		Coil	030	2	6	3	2	2	2	1	2.2.6.3.2.2	3.x.6.3.2.2
		Battery	031	2	4	2	3	2	3	1	2.2.4.2.3.3	3.x.4.2.3.2
		PCB	033	3	1	1	1	1	5	4	2.3.1.1.1.5	3.x.1.1.1.1
		SMA	037	3	2	2	2	1	4	1	2.3.2.2.2.4	3.x.2.2.2.1
		Plunger	013	2	4	3	3	2	5	2	2.2.4.3.3.5	3.x.4.3.3.2
		Cap 1	007	2	4	3	3	2	3	2	2.2.4.3.3.3	3.x.4.3.3.2
Diagnose Pill	RP03	Body 1	001	2	4	4	3	3	3	2	2.2.4.4.3.3	3.x.4.4.3.3
		Coil	030	2	6	3	2	2	2	1	2.2.6.3.2.2	3.x.6.3.2.2
		Battery	031	2	4	2	3	2	3	1	2.2.4.2.3.3	3.x.4.2.3.2
		PCB	034	3	1	1	1	1	5	4	2.3.1.1.1.5	3.x.1.1.1.1
		Membrane	022	3	3	1	1	1	2	2	2.3.3.1.1.2	3.x.3.1.1.1
		Sensor	036	3	1	1	1	1	5	3	2.3.1.1.1.5	3.x.1.1.1.1
		Cap 2	008	2	4	3	3	2	3	2	2.2.4.3.3.3	3.x.4.3.3.2
Fluid Separator	RP04	Body 3	003	2	4	4	3	3	3	2	2.2.4.4.3.3	3.x.4.4.3.3
		Feature Block 1	014	2	4	3	3	2	3	2	2.2.4.3.3.3	3.x.4.3.3.2
		Feature Block 1	014	2	4	3	3	2	3	2	2.2.4.3.3.3	3.x.4.3.3.2
		Feature Block 1	014	2	4	3	3	2	3	2	2.2.4.3.3.3	3.x.4.3.3.2
		Lid	009	2	4	3	3	2	3	2	2.2.4.3.3.3	3.x.4.3.3.2
Micropump	RP05	Body w coil	004	3	4	5	3	3	3	2	2.3.4.5.3.3	3.x.4.5.3.3
		Magnet case	015	3	4	5	3	3	2	2	2.3.4.5.3.2	3.x.4.5.3.3
		Magnet	018	3	4	5	3	3	2	1	2.3.4.5.3.2	3.x.4.5.3.3
		Pump shaft	019	3	4	4	3	3	3	1	2.3.4.4.3.3	3.x.4.4.3.3
		Port	010	3	4	4	3	2	3	2	2.3.4.4.3.3	3.x.4.4.3.3
Acoustic Amplifier	RP06	Body 4	005	2	4	3	3	3	3	2	2.2.4.3.3.3	3.x.4.3.3.3
		Plate seat	016	2	4	2	2	2	3	2	2.2.4.2.2.3	3.x.4.2.2.2
		Plate	017	2	3	2	2	1	3	2	2.2.3.2.2.3	3.x.3.2.2.1
		Membrane 1	020	3	3	2	1	1	2	2	2.3.3.2.1.2	3.x.3.2.1.1
		membrane 2	021	3	3	1	1	1	2	2	2.3.3.1.1.2	3.x.3.1.1.1
		Clip 1	011	2	3	2	2	1	3	2	2.2.3.2.2.3	3.x.3.2.2.1
		Clip 2	012	2	3	1	2	1	3	2	2.2.3.1.2.3	3.x.3.1.2.1

Figure 16-2: Capability Definitions for the components in Test Case 2



RP01	001	030	031	032	035	006
001	■	1				2
030	░	■		3		
031	░	░	■	4		
032	░	░	░	■	5	
035	░	░	░	░	■	6
006	░	░	░	░	░	■

RP02	002	030	031	033	037	013	007
002	■	1					2
030	░	■		3			
031	░	░	■	4			
033	░	░	░	■	5		
037	░	░	░	░	■	6	
013	░	░	░	░	░	■	
007	░	░	░	░	░	░	■

RP03	001	030	031	034	022	036	008
001	■	1			2		3
030	░	■		4			
031	░	░	■	5			
034	░	░	░	■	6	7	
022	░	░	░	░	■	8	
036	░	░	░	░	░	■	
008	░	░	░	░	░	░	■

RP04	003	014	014	014	009
003	■	1	2	3	4
014	░	■	5		
014	░	░	■	6	
014	░	░	░	■	7
009	░	░	░	░	■

RP05	004	015	018	019	010
004	■	1			2
015	░	■	3		
018	░	░	■	4	
019	░	░	░	■	5
010	░	░	░	░	■

RP06	005	016	017	020	021	011	012
005	■	1		2	3	4	5
016	░	■	6				
017	░	░	■				
020	░	░	░	■		7	
021	░	░	░	░	■		8
011	░	░	░	░	░	■	
012	░	░	░	░	░	░	■

Liason Ref	Liason Definition	Join Capability
RP01.1	4.2.3.2.4.2.1.2	4.2.3.2.4.2.1.2
RP01.2	4.3.3.1.2.4.1.1	4.3.3.1.2.4.1.1
RP01.3	4.1.2.2.5.4.1.1	4.1.2.2.5.4.1.1
RP01.4	4.1.2.2.5.4.1.1	4.1.2.2.5.4.1.1
RP01.5	4.2.1.2.3.1.1.1	4.2.1.2.3.1.1.1
RP01.6	contact	contact
RP02.1	4.3.3.1.2.4.1.1	4.3.3.1.2.4.1.1
RP02.2	4.2.3.2.4.2.1.2	4.2.3.2.4.2.1.2
RP02.3	4.2.1.2.3.1.1.1	4.2.1.2.3.1.1.1
RP02.4	4.1.2.2.5.4.1.1	4.1.2.2.5.4.1.1
RP02.5	4.2.3.2.4.1.3.1	4.2.3.2.4.1.3.1
RP02.6	4.2.3.2.4.4.3.1	4.2.3.2.4.4.3.1
RP03.1	4.2.3.2.4.2.1.2	4.2.3.2.4.2.1.2
RP03.2	4.2.3.2.2.2.2.3	4.2.3.2.2.2.2.3
RP03.3	4.3.3.1.2.4.1.1	4.3.3.1.2.4.1.1
RP03.4	4.2.1.2.3.1.1.1	4.2.1.2.3.1.1.1
RP03.5	4.2.3.2.1.2.1.3	4.2.3.2.1.2.1.3
RP03.6	contact	contact
RP03.7	4.1.2.2.5.4.1.1	4.1.2.2.5.4.1.1
RP03.8	4.1.2.2.5.4.1.1	4.1.2.2.5.4.1.1
RP04.1	4.1.2.1.2.2.1.1	4.1.2.1.2.2.1.1
RP04.2	4.1.2.1.2.2.1.1	4.1.2.1.2.2.1.1
RP04.3	4.1.2.1.2.2.1.1	4.1.2.1.2.2.1.1
RP04.4	4.2.2.1.4.2.1.2	4.2.2.1.4.2.1.2
RP04.5	contact	contact
RP04.6	contact	contact
RP04.7	contact	contact
RP05.1	4.1.2.1.2.4.1.1	4.1.2.1.2.4.1.1
RP05.2	4.2.3.2.4.2.1.2	4.2.3.2.4.2.1.2
RP05.3	4.2.2.3.2.1.3.1	4.2.2.3.2.1.3.1
RP05.4	4.2.2.3.2.1.3.1	4.2.2.3.2.1.3.1
RP05.5	contact	contact
RP06.1	4.3.2.2.2.2.2.1	4.3.2.2.2.2.2.1
RP06.2	4.3.2.2.2.2.2.1	4.3.2.2.2.2.2.1
RP06.3	4.2.3.1.1.2.1.2	4.2.3.1.1.2.1.2
RP06.4	4.1.2.1.6.2.1.1	4.1.2.1.6.2.1.1
RP06.5	contact	contact
RP06.6	4.2.3.1.1.2.1.2	4.2.3.1.1.2.1.2
RP06.7	4.2.3.1.1.2.1.2	4.2.3.1.1.2.1.2
RP06.8	contact	contact

Figure 16-3: Identification and Definition of Product Liaisons, leading to definition of the required Joining capabilities

16.1.6 Identification of the Available Capabilities

Using the previously defined process for the identification of equipment-based capabilities, the link between the existing modules and the Available Capabilities is derived, shown in Figure 16-4.

Module Name	Description	Module Type	Module Ref	Interfaces		Cap Class	Cap Ref	Cap Def	Cap Links
				Mounting	Tooling				
SCARA	SCARA Robot with auto tool changer	Robot	Mod A	Bay A	ATC	Move	C_E01	1.1.39.2.2.2	α
Linear actuators	2 axis liner robotic stage with manual tool changer	Robot	Mod B	Bay A	MTC	Move	C_E02	1.1.5.1.3.3	β
Gripper 1	mechanical gripper, 3 fingered for cylindrical	Gripper	Mod C	MTC	n/a	Retain	C_E03	3.1.4.2.3.3	β
Gripper 2	mechanical gripper, 4 fingered for cubic parts	Gripper	Mod D	ATC	n/a	Retain	C_E04	3.1.2.2.3.3	α
Bowl feeder	bowl feeder for cylindrical parts	Feeder	Mod E	Floor	n/a	Feed	C_E05	2.2.4.2.3	n/a
Tray feeder	tray feeder for cubic parts	Feeder	Mod F	Floor	n/a	Feed	C_E06	2.3.2.2.1	n/a
Conveyor	6-station conveyor unit	Conveyor	Mod G	Bay B	n/a	Move	C_E07	3.2.2.2.2.3	n/a
	Emergent capability A		α	Mod A	Mod D	Join	C_E08	4.1.2.x.2.x.2.1	n/a
	Emergent capability B		β	Mod B	Mod C	Join	C_E09	4.1.2.x.2.x.2.1	n/a

Figure 16-4: Summary of the existing equipment modules and their associated capabilities

16.1.7 Definition of Available Capabilities

This is performed according to the previously-used method and delivers the information summarised in Figure 16-5.

Module Name	Description	Module Type	Module Ref	Cap Ref	Cap Def	Cap Links
SCARA	SCARA Robot with auto tool changer	Robot	Mod A	CE01	1.1.39.2.2.2	α
Linear actuators	2 axis liner robotic stage with manual tool changer	Robot	Mod B	CE02	1.1.5.1.3.3	β
Gripper 1	mechanical gripper, 3 fingered for cylindrical parts	Gripper	Mod C	CE03	3.1.4.2.3.3	β
Gripper 2	mechanical gripper, 4 fingered for cubic parts	Gripper	Mod D	CE04	3.1.2.2.3.3	α
Bowl feeder	bowl feeder for cylindrical parts	Feeder	Mod E	CE05	2.2.4.2.3	n/a
Tray feeder	tray feeder for cubic parts	Feeder	Mod F	CE06	2.3.2.2.1	n/a
Conveyor	6-station conveyor unit	Conveyor	Mod G	CE07	3.2.2.2.2.3	n/a
	Emergent capability A		α	CE08	4.1.2.x.2.x.2.1	n/a
	Emergent capability B		β	CE09	4.1.2.x.2.x.2.1	n/a

Figure 16-5: Summary of the defined capabilities against the associated modules

16.1.8 Identification of Required Capabilities

The PFD Template is used to create the PFD and to identify the class and location of the Required Capabilities These PFDs are shown in Figures 16-6 to 16-11

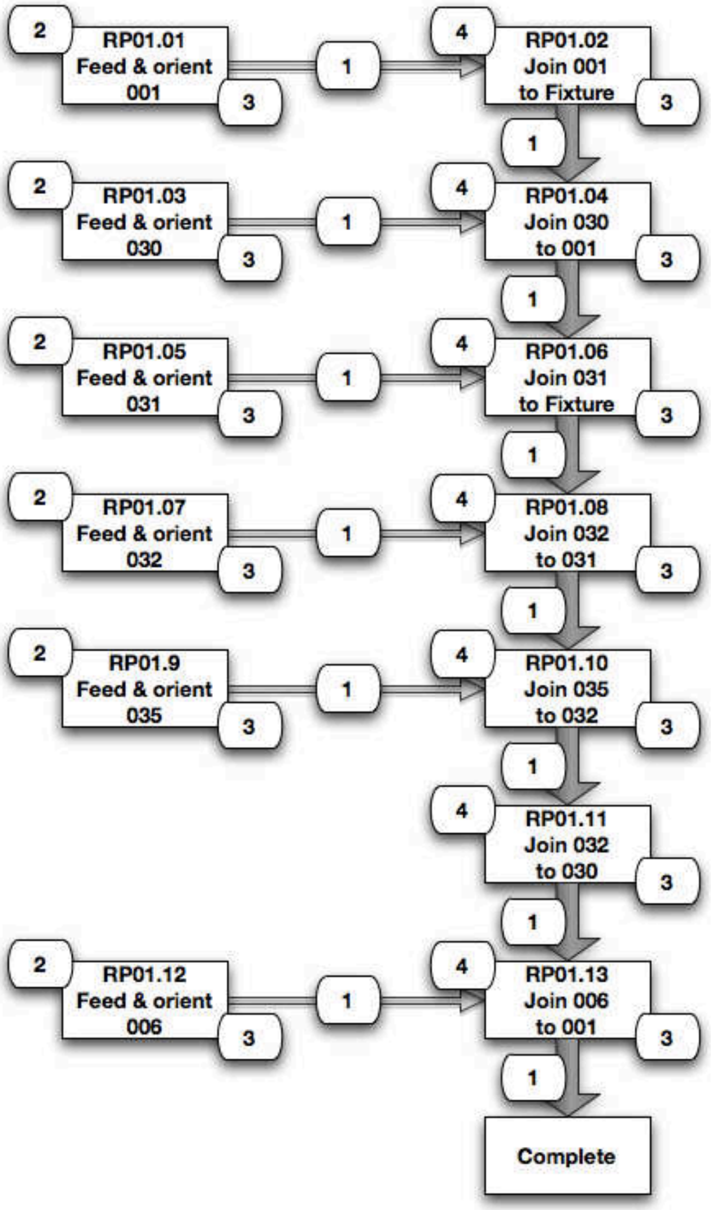


Figure 16-6: The PFD for the Camera Pill

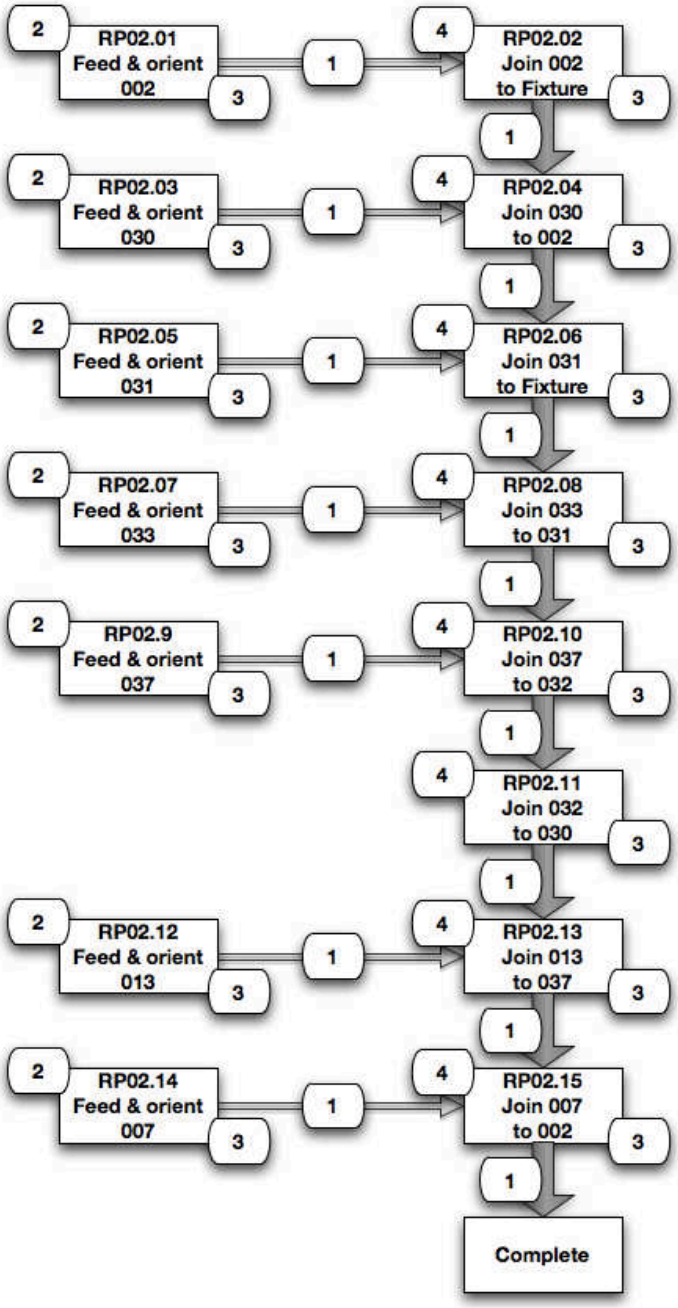


Figure 16-7: The PFD for the Dispense Pill

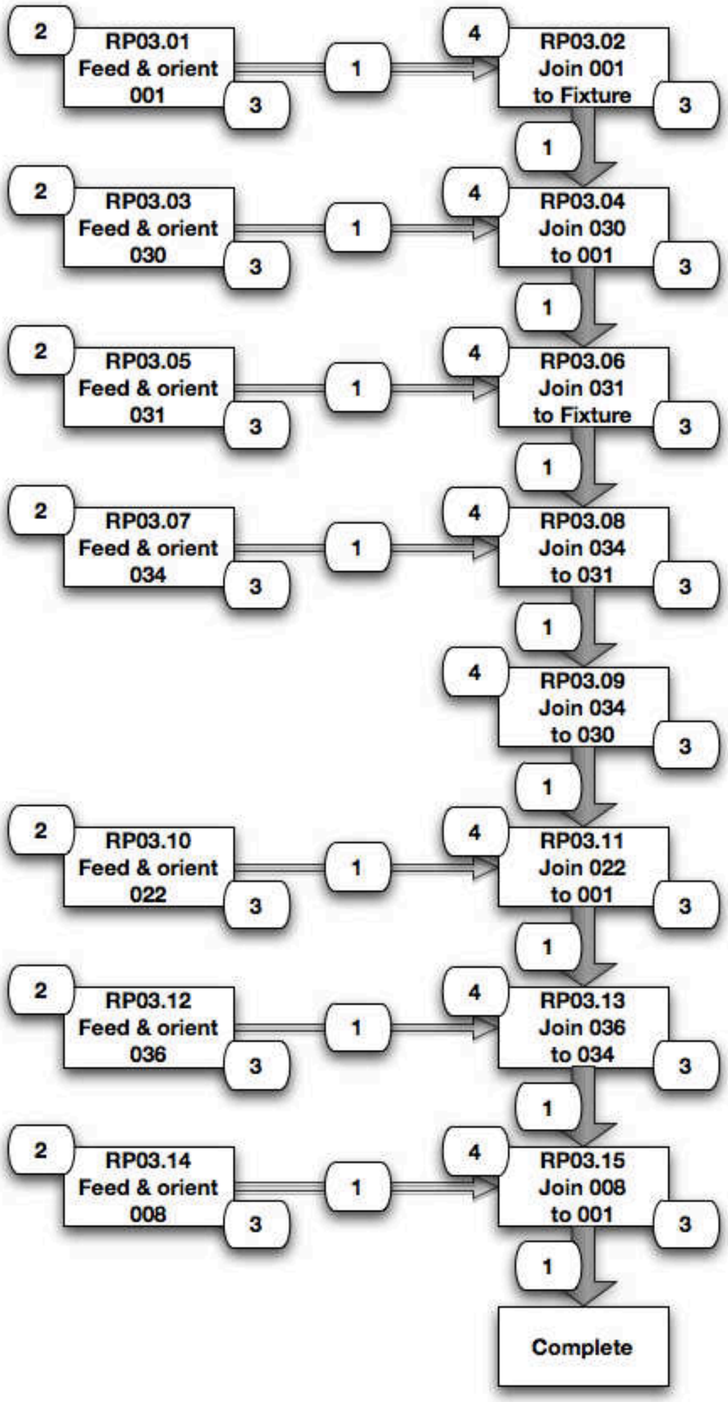


Figure 16-8: The PFD for the Diagnose Pill

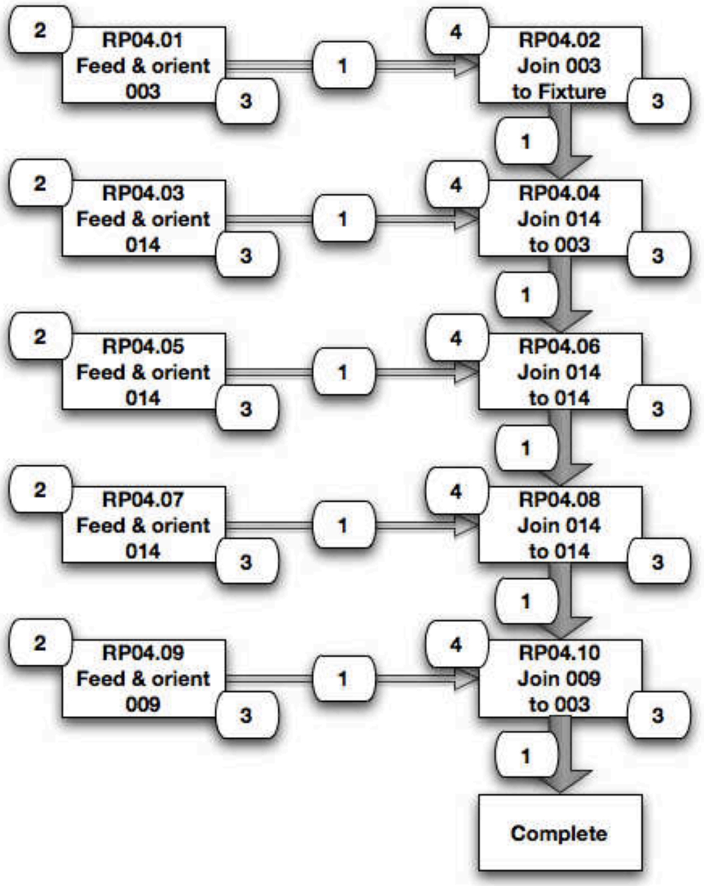


Figure 16-9: The PFD for the Fluidics Separator

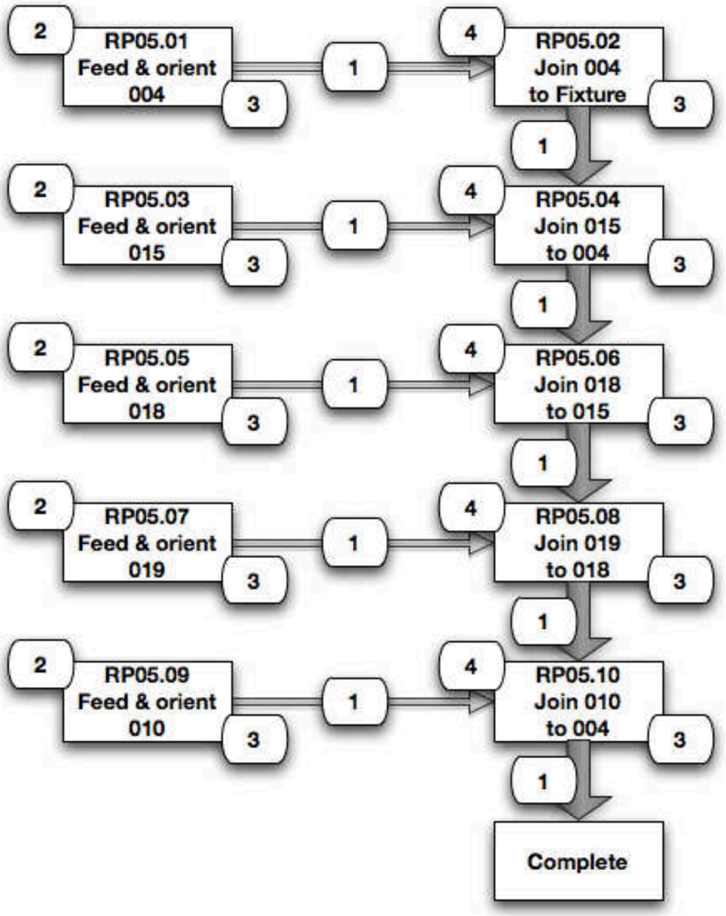


Figure 16-10: The PFD for the Micro Pump

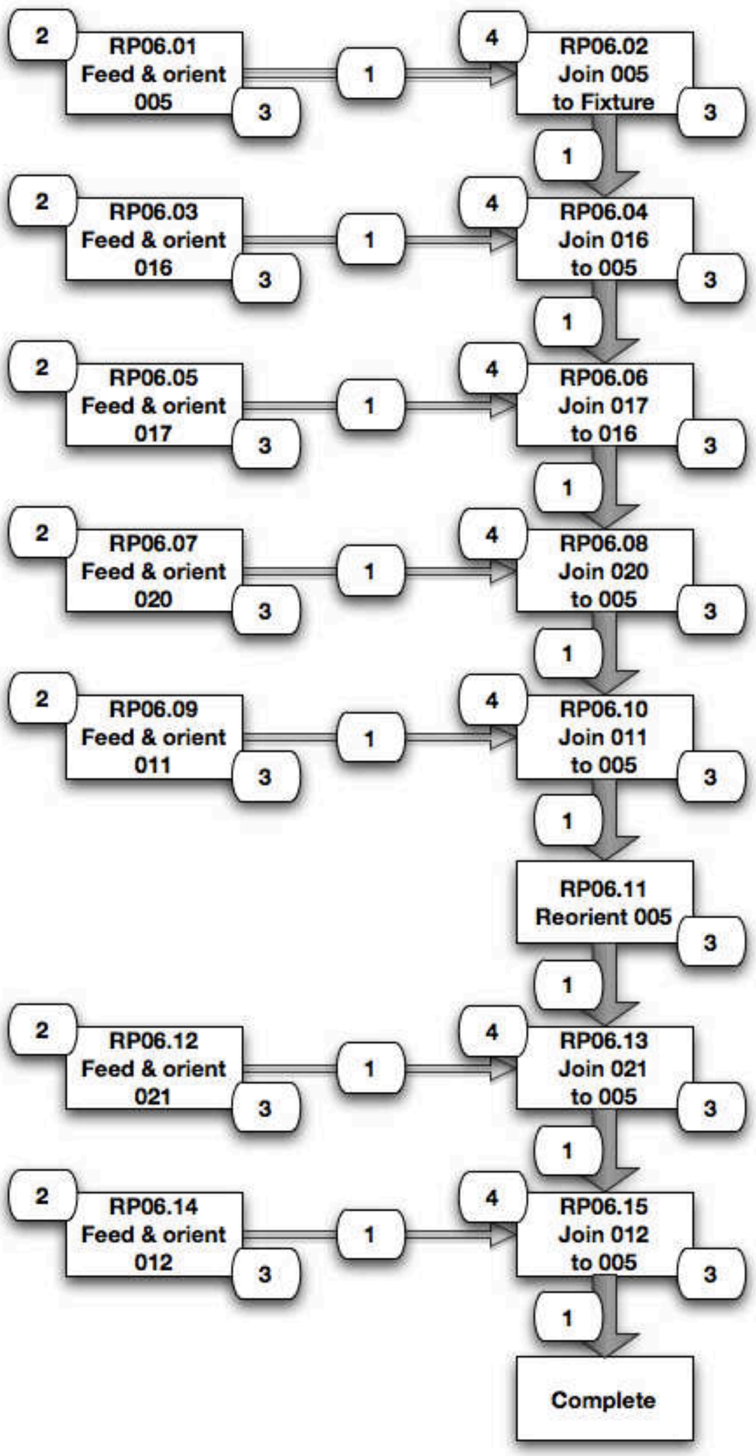


Figure 16-11: PFD for the Acoustic Amplifier

16.1.9 Definition of Required Capabilities

This step utilises the previously defined components and liaisons in accordance with the following rules:

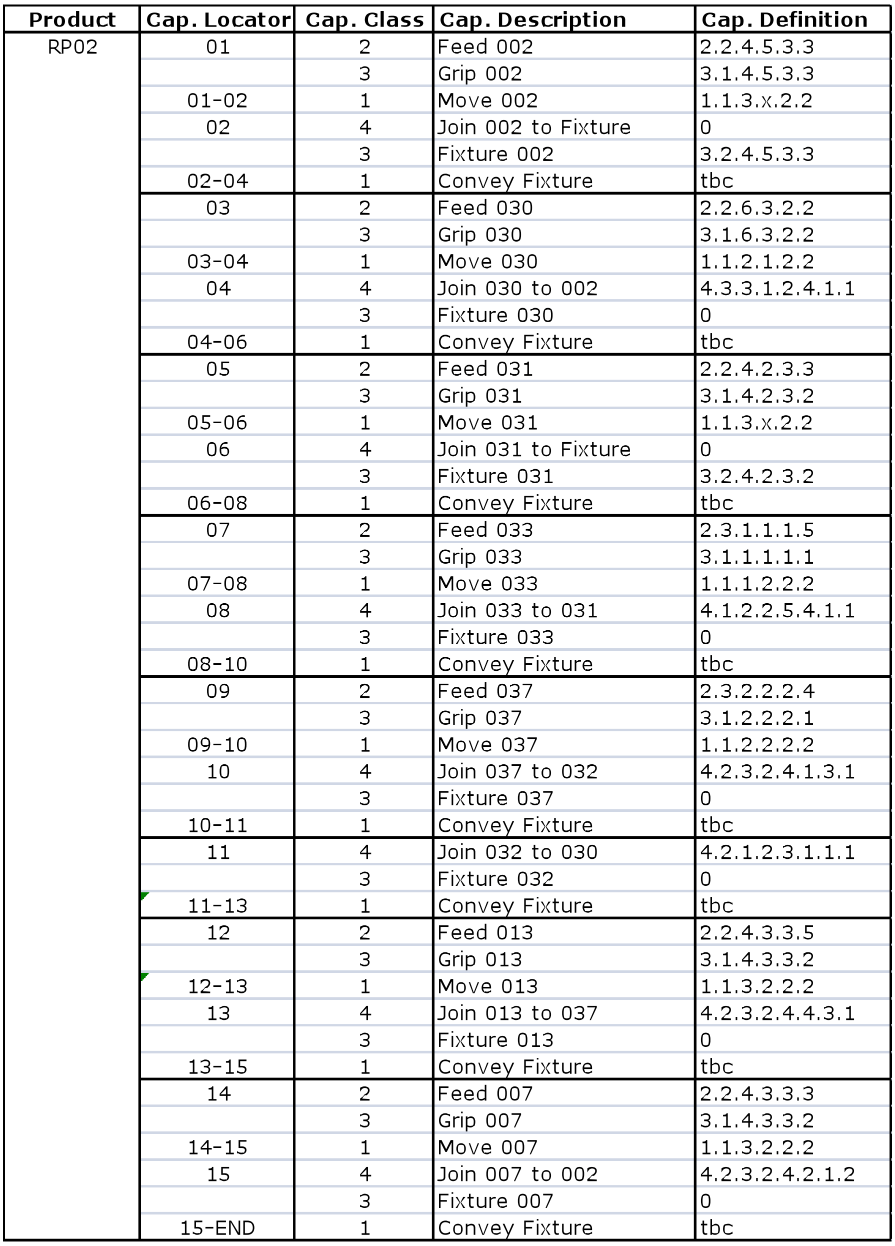
- Motion capabilities are dictated by;
    - System framework,

  - Final system layout,
  - Component Strength
  - Liaison Precision
- Feeding Capabilities are dictated by;
  - Relevant component factors
- Retaining Capabilities are dictated by;
  - Relevant component factors
- Joining Capabilities are dictated by
  - Relevant liaison definition

This leads to the creation and population of a table for each required product, which are shown in Figures 16-12 to 16-17.

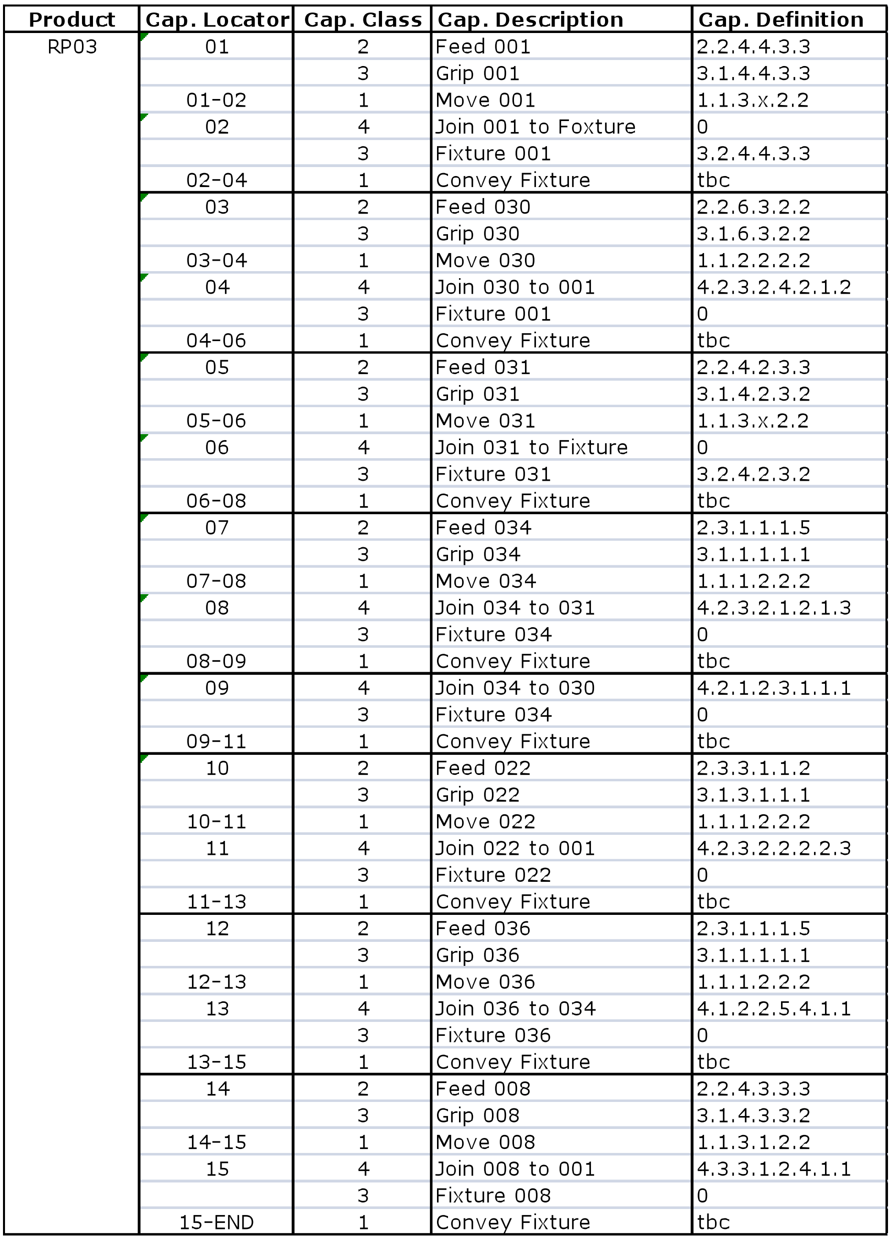
Product	Cap Locator	Cap Class	Cap Description	Cap Definition
RP01	01	2	Feed 001	2.2.4.4.3.3
		3	Grip 001	3.1.4.4.3.3
	01-02	1	Move 001	1.1.3.x.2.2
	02	4	Join 001 to Fixture	0
		3	Fixture 001	3.2.4.4.3.3
	02-04	1	Convey fixture	tbc
	03	2	Feed 030	2.2.6.3.2.2
		3	Grip 030	3.1.6.3.2.2
	03-04	1	Move 030	1.1.2.2.2.2
	04	4	Join 030 to 001	4.2.3.2.4.2.1.2
		3	Fixture 030	0
	04-06	1	Convey fixture	tbc
	05	2	Feed 031	2.2.4.2.3.3
		3	Grip 031	3.1.4.2.3.2
	05-06	1	Move 031	1.1.3.x.2.2
	06	4	Join 031 to Fixture	0
		3	Fixture 031	3.2.4.2.3.2
	06-08	1	Convey fixture	tbc
	07	2	Feed 032	2.3.1.1.1.5
		3	Grip 032	3.1.1.1.1.1
	07-08	1	Move 032	1.1.1.2.2.2
	08	4	Join 032 to 031	4.1.2.2.5.4.1.1
		3	Fixture 032	0
	08-10	1	Convey fixture	tbc
	09	2	Feed 035	2.3.2.2.2.5
		3	Grip 035	3.1.2.2.2.2
	09-10	1	Move 035	1.1.2.2.2.2
	10	4	Join 035 to 032	4.2.1.2.3.1.1.1
		3	Fixture 035	0
	10-11	1	Convey fixture	tbc
	11	4	Join 032 to 030	4.1.2.2.5.4.1.1
		3	Fixture 032	0
	11-13	1	Convey fixture	tbc
	12	2	Feed 006	2.3.4.3.3.3
		3	Grip 006	3.1.4.3.3.2
	12-13	1	Move 006	1.1.3.1.2.2
	13	4	Join 006 to 001	4.3.3.1.2.4.1.1
		3	Foxture 006	0
	13-END	1	Convey fixture	tbc

Figure 16-12: Full Capability definition for the Camera Pill



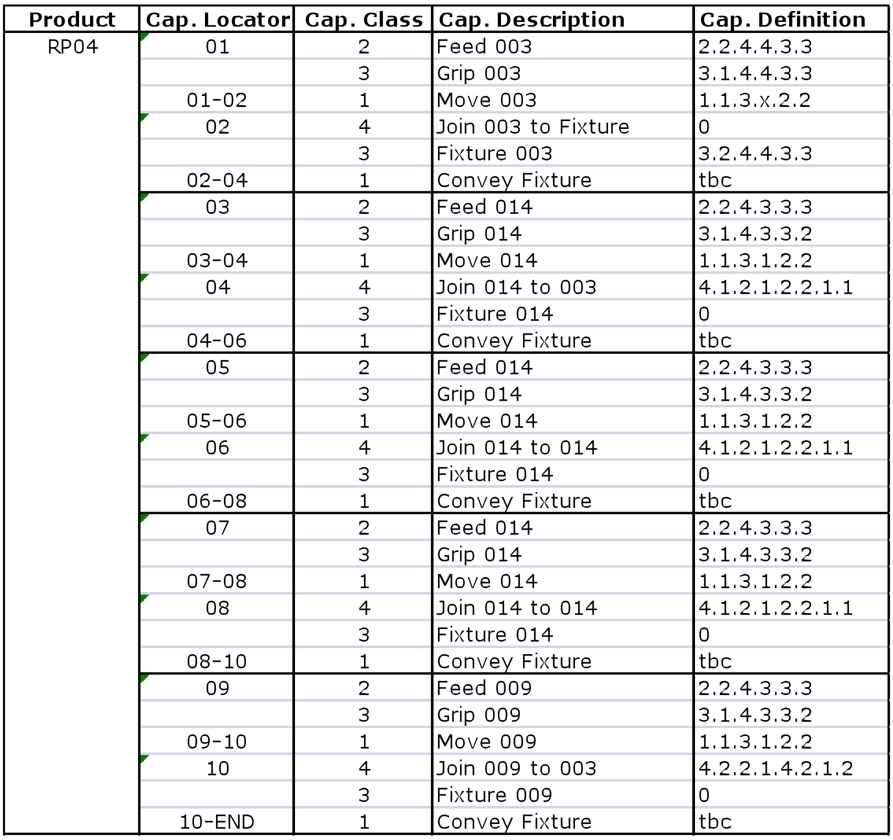
Product	Cap. Locator	Cap. Class	Cap. Description	Cap. Definition
RP02	01	2	Feed 002	2.2.4.5.3.3
		3	Grip 002	3.1.4.5.3.3
	01-02	1	Move 002	1.1.3.x.2.2
	02	4	Join 002 to Fixture	0
		3	Fixture 002	3.2.4.5.3.3
	02-04	1	Convey Fixture	tbc
	03	2	Feed 030	2.2.6.3.2.2
		3	Grip 030	3.1.6.3.2.2
	03-04	1	Move 030	1.1.2.1.2.2
	04	4	Join 030 to 002	4.3.3.1.2.4.1.1
		3	Fixture 030	0
	04-06	1	Convey Fixture	tbc
	05	2	Feed 031	2.2.4.2.3.3
		3	Grip 031	3.1.4.2.3.2
	05-06	1	Move 031	1.1.3.x.2.2
	06	4	Join 031 to Fixture	0
		3	Fixture 031	3.2.4.2.3.2
	06-08	1	Convey Fixture	tbc
	07	2	Feed 033	2.3.1.1.1.5
		3	Grip 033	3.1.1.1.1.1
	07-08	1	Move 033	1.1.1.2.2.2
	08	4	Join 033 to 031	4.1.2.2.5.4.1.1
		3	Fixture 033	0
	08-10	1	Convey Fixture	tbc
	09	2	Feed 037	2.3.2.2.2.4
		3	Grip 037	3.1.2.2.2.1
	09-10	1	Move 037	1.1.2.2.2.2
	10	4	Join 037 to 032	4.2.3.2.4.1.3.1
		3	Fixture 037	0
	10-11	1	Convey Fixture	tbc
	11	4	Join 032 to 030	4.2.1.2.3.1.1.1
		3	Fixture 032	0
	11-13	1	Convey Fixture	tbc
	12	2	Feed 013	2.2.4.3.3.5
		3	Grip 013	3.1.4.3.3.2
	12-13	1	Move 013	1.1.3.2.2.2
	13	4	Join 013 to 037	4.2.3.2.4.4.3.1
		3	Fixture 013	0
	13-15	1	Convey Fixture	tbc
	14	2	Feed 007	2.2.4.3.3.3
		3	Grip 007	3.1.4.3.3.2
	14-15	1	Move 007	1.1.3.2.2.2
	15	4	Join 007 to 002	4.2.3.2.4.2.1.2
		3	Fixture 007	0
	15-END	1	Convey Fixture	tbc

Figure 16-13: Full Capability definition for the Dispense Pill



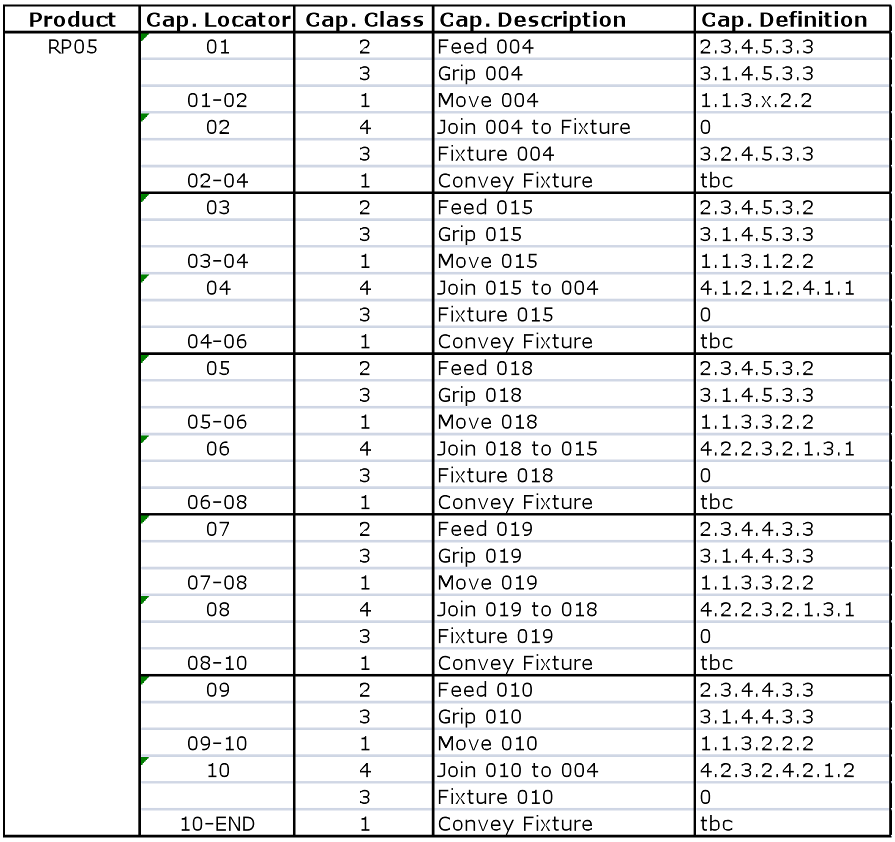
Product	Cap. Locator	Cap. Class	Cap. Description	Cap. Definition
RP03	01	2	Feed 001	2.2.4.4.3.3
		3	Grip 001	3.1.4.4.3.3
	01-02	1	Move 001	1.1.3.x.2.2
	02	4	Join 001 to Foxture	0
		3	Fixture 001	3.2.4.4.3.3
	02-04	1	Convey Fixture	tbc
	03	2	Feed 030	2.2.6.3.2.2
		3	Grip 030	3.1.6.3.2.2
	03-04	1	Move 030	1.1.2.2.2.2
	04	4	Join 030 to 001	4.2.3.2.4.2.1.2
		3	Fixture 001	0
	04-06	1	Convey Fixture	tbc
	05	2	Feed 031	2.2.4.2.3.3
		3	Grip 031	3.1.4.2.3.2
	05-06	1	Move 031	1.1.3.x.2.2
	06	4	Join 031 to Fixture	0
		3	Fixture 031	3.2.4.2.3.2
	06-08	1	Convey Fixture	tbc
	07	2	Feed 034	2.3.1.1.1.5
		3	Grip 034	3.1.1.1.1.1
	07-08	1	Move 034	1.1.1.2.2.2
	08	4	Join 034 to 031	4.2.3.2.1.2.1.3
		3	Fixture 034	0
	08-09	1	Convey Fixture	tbc
	09	4	Join 034 to 030	4.2.1.2.3.1.1.1
		3	Fixture 034	0
	09-11	1	Convey Fixture	tbc
	10	2	Feed 022	2.3.3.1.1.2
		3	Grip 022	3.1.3.1.1.1
	10-11	1	Move 022	1.1.1.2.2.2
	11	4	Join 022 to 001	4.2.3.2.2.2.2.3
		3	Fixture 022	0
	11-13	1	Convey Fixture	tbc
	12	2	Feed 036	2.3.1.1.1.5
		3	Grip 036	3.1.1.1.1.1
	12-13	1	Move 036	1.1.1.2.2.2
	13	4	Join 036 to 034	4.1.2.2.5.4.1.1
		3	Fixture 036	0
	13-15	1	Convey Fixture	tbc
	14	2	Feed 008	2.2.4.3.3.3
		3	Grip 008	3.1.4.3.3.2
	14-15	1	Move 008	1.1.3.1.2.2
	15	4	Join 008 to 001	4.3.3.1.2.4.1.1
		3	Fixture 008	0
	15-END	1	Convey Fixture	tbc

Figure 16-14: Full Capability definition for the Diagnose Pill



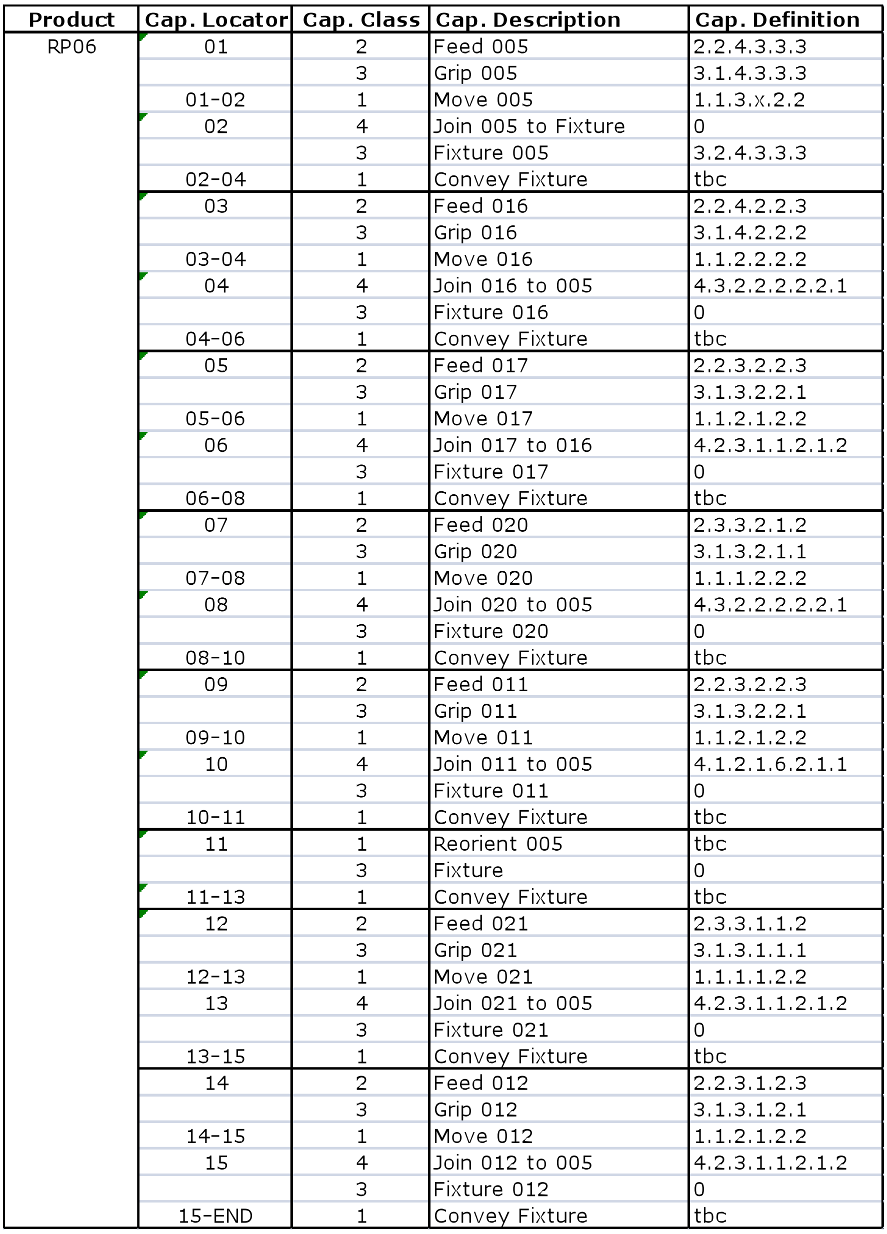
Product	Cap. Locator	Cap. Class	Cap. Description	Cap. Definition
RP04	01	2	Feed 003	2.2.4.4.3.3
		3	Grip 003	3.1.4.4.3.3
	01-02	1	Move 003	1.1.3.x.2.2
	02	4	Join 003 to Fixture	0
		3	Fixture 003	3.2.4.4.3.3
	02-04	1	Convey Fixture	tbc
	03	2	Feed 014	2.2.4.3.3.3
		3	Grip 014	3.1.4.3.3.2
	03-04	1	Move 014	1.1.3.1.2.2
	04	4	Join 014 to 003	4.1.2.1.2.2.1.1
		3	Fixture 014	0
	04-06	1	Convey Fixture	tbc
	05	2	Feed 014	2.2.4.3.3.3
		3	Grip 014	3.1.4.3.3.2
	05-06	1	Move 014	1.1.3.1.2.2
	06	4	Join 014 to 014	4.1.2.1.2.2.1.1
		3	Fixture 014	0
	06-08	1	Convey Fixture	tbc
	07	2	Feed 014	2.2.4.3.3.3
		3	Grip 014	3.1.4.3.3.2
	07-08	1	Move 014	1.1.3.1.2.2
	08	4	Join 014 to 014	4.1.2.1.2.2.1.1
		3	Fixture 014	0
	08-10	1	Convey Fixture	tbc
	09	2	Feed 009	2.2.4.3.3.3
		3	Grip 009	3.1.4.3.3.2
	09-10	1	Move 009	1.1.3.1.2.2
	10	4	Join 009 to 003	4.2.2.1.4.2.1.2
		3	Fixture 009	0
	10-END	1	Convey Fixture	tbc

Figure 16-15: Full Capability definition for the Fluidics Separator



Product	Cap. Locator	Cap. Class	Cap. Description	Cap. Definition
RP05	01	2	Feed 004	2.3.4.5.3.3
		3	Grip 004	3.1.4.5.3.3
	01-02	1	Move 004	1.1.3.x.2.2
	02	4	Join 004 to Fixture	0
		3	Fixture 004	3.2.4.5.3.3
	02-04	1	Convey Fixture	tbc
	03	2	Feed 015	2.3.4.5.3.2
		3	Grip 015	3.1.4.5.3.3
	03-04	1	Move 015	1.1.3.1.2.2
	04	4	Join 015 to 004	4.1.2.1.2.4.1.1
		3	Fixture 015	0
	04-06	1	Convey Fixture	tbc
	05	2	Feed 018	2.3.4.5.3.2
		3	Grip 018	3.1.4.5.3.3
	05-06	1	Move 018	1.1.3.3.2.2
	06	4	Join 018 to 015	4.2.2.3.2.1.3.1
		3	Fixture 018	0
	06-08	1	Convey Fixture	tbc
	07	2	Feed 019	2.3.4.4.3.3
		3	Grip 019	3.1.4.4.3.3
	07-08	1	Move 019	1.1.3.3.2.2
	08	4	Join 019 to 018	4.2.2.3.2.1.3.1
		3	Fixture 019	0
	08-10	1	Convey Fixture	tbc
	09	2	Feed 010	2.3.4.4.3.3
		3	Grip 010	3.1.4.4.3.3
	09-10	1	Move 010	1.1.3.2.2.2
	10	4	Join 010 to 004	4.2.3.2.4.2.1.2
		3	Fixture 010	0
	10-END	1	Convey Fixture	tbc

Figure 16-16: Full Capability definition for the Micro Pump



Product	Cap. Locator	Cap. Class	Cap. Description	Cap. Definition
RP06	01	2	Feed 005	2.2.4.3.3.3
		3	Grip 005	3.1.4.3.3.3
	01-02	1	Move 005	1.1.3.x.2.2
	02	4	Join 005 to Fixture	0
		3	Fixture 005	3.2.4.3.3.3
	02-04	1	Convey Fixture	tbc
	03	2	Feed 016	2.2.4.2.2.3
		3	Grip 016	3.1.4.2.2.2
	03-04	1	Move 016	1.1.2.2.2.2
	04	4	Join 016 to 005	4.3.2.2.2.2.2.1
		3	Fixture 016	0
	04-06	1	Convey Fixture	tbc
	05	2	Feed 017	2.2.3.2.2.3
		3	Grip 017	3.1.3.2.2.1
	05-06	1	Move 017	1.1.2.1.2.2
	06	4	Join 017 to 016	4.2.3.1.1.2.1.2
		3	Fixture 017	0
	06-08	1	Convey Fixture	tbc
	07	2	Feed 020	2.3.3.2.1.2
		3	Grip 020	3.1.3.2.1.1
	07-08	1	Move 020	1.1.1.2.2.2
	08	4	Join 020 to 005	4.3.2.2.2.2.2.1
		3	Fixture 020	0
	08-10	1	Convey Fixture	tbc
	09	2	Feed 011	2.2.3.2.2.3
		3	Grip 011	3.1.3.2.2.1
	09-10	1	Move 011	1.1.2.1.2.2
	10	4	Join 011 to 005	4.1.2.1.6.2.1.1
		3	Fixture 011	0
	10-11	1	Convey Fixture	tbc
	11	1	Reorient 005	tbc
		3	Fixture	0
	11-13	1	Convey Fixture	tbc
	12	2	Feed 021	2.3.3.1.1.2
		3	Grip 021	3.1.3.1.1.1
	12-13	1	Move 021	1.1.1.1.2.2
	13	4	Join 021 to 005	4.2.3.1.1.2.1.2
		3	Fixture 021	0
	13-15	1	Convey Fixture	tbc
	14	2	Feed 012	2.2.3.1.2.3
		3	Grip 012	3.1.3.1.2.1
	14-15	1	Move 012	1.1.2.1.2.2
	15	4	Join 012 to 005	4.2.3.1.1.2.1.2
		3	Fixture 012	0
	15-END	1	Convey Fixture	tbc

Figure 16-17: Full Capability definition for the Acoustic Amplifier

16.1.10 Capability Comparison

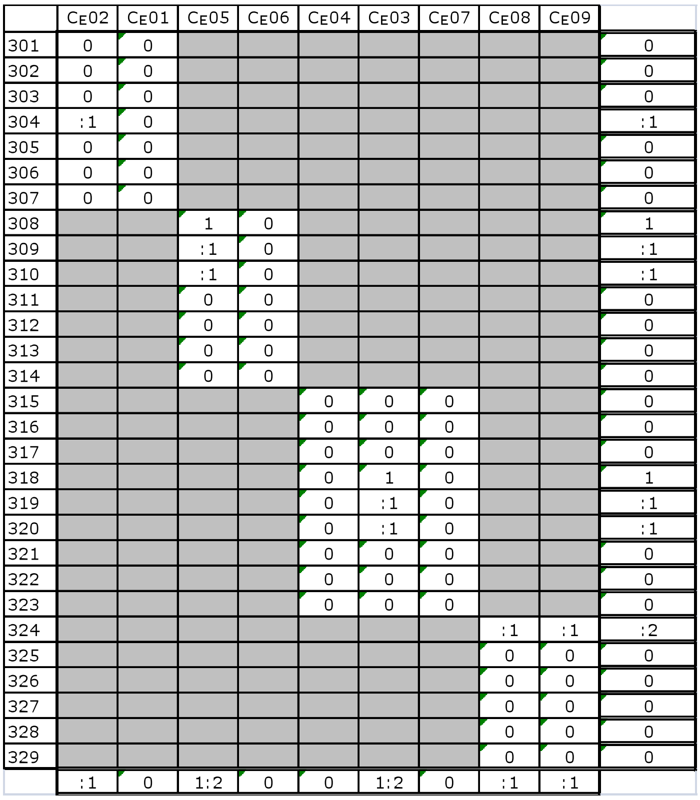
Using the capability definitions, each required set can be compared against the available set. Thus the Comparison Matrices are created and populated and are shown in Figures 16-18 to 16-23

	CE02	CE01	CE05	CE06	CE04	CE03	CE07	CE08	CE09	
101	:1	1								1:1
102	:1	1								1:1
103	:1	1								1:1
104	0	1								1
105	0	:1								:1
106	0	:1								:1
107			1	0						1
108			:1	0						:1
109			0	0						0
110			0	0						0
111			0	:1						:1
112			0	0						0
113					0	0	0			0
114					1	0	0			1
115					0	:1	0			:1
116					0	:1	0			:1
117					0	:1	0			:1
118					0	0	0			0
119					0	0	0			0
120					0	0	0			0
121								:1	:1	:2
122								:1	:1	:2
123								0	0	0
124								0	0	0
125								0	0	0
	:3	4:2	1:1	:1	1	:3	0	:2	:2	

Figure 16-18: Comparison Matrix for the Camera Pill

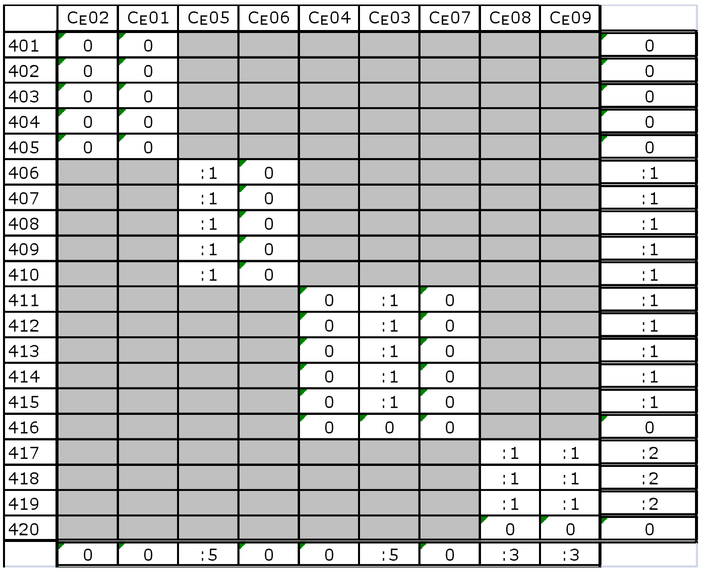
	CE02	CE01	CE05	CE06	CE04	CE03	CE07	CE08	CE09	
201	0	0								0
202	1	0								1
203	:1	0								:1
204	0	0								0
205	0	0								0
206	0	0								0
207	0	0								0
208			1	0						1
209			:1	0						:1
210			:1	0						:1
211			:1	0						:1
212			0	0						0
213			0	0						0
214			0	:1						:1
215					0	0	0			0
216					1	0	0			1
217					0	1	0			1
218					0	:1	0			:1
219					0	:1	0			:1
220					0	:1	0			:1
221					0	:1	0			:1
222					0	0	0			0
223					0	0	0			0
224								:1	:1	:2
225								0	0	0
226								0	0	0
227								0	0	0
228								0	0	0
229								0	0	0
	1:1	0	1:3	:1	1	1:4	0	:1	:1	

Figure 16-19: Comparison Matrix for the Dispense Pill



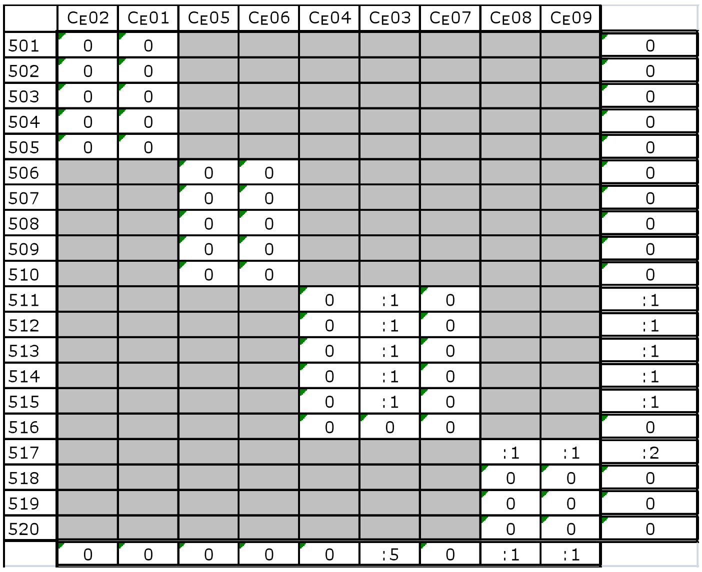
	CE02	CE01	CE05	CE06	CE04	CE03	CE07	CE08	CE09	
301	0	0								0
302	0	0								0
303	0	0								0
304	:1	0								:1
305	0	0								0
306	0	0								0
307	0	0								0
308			1	0						1
309			:1	0						:1
310			:1	0						:1
311			0	0						0
312			0	0						0
313			0	0						0
314			0	0						0
315					0	0	0			0
316					0	0	0			0
317					0	0	0			0
318					0	1	0			1
319					0	:1	0			:1
320					0	:1	0			:1
321					0	0	0			0
322					0	0	0			0
323					0	0	0			0
324								:1	:1	:2
325								0	0	0
326								0	0	0
327								0	0	0
328								0	0	0
329								0	0	0
	:1	0	1:2	0	0	1:2	0	:1	:1	

Figure 16-20: Comparison Matrix for the Diagnose Pill



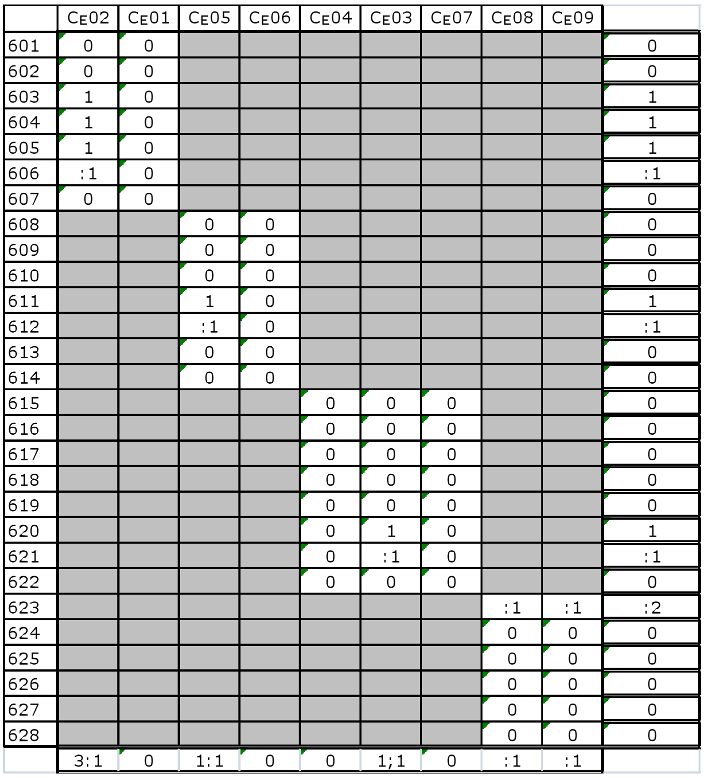
	CE02	CE01	CE05	CE06	CE04	CE03	CE07	CE08	CE09	
401	0	0								0
402	0	0								0
403	0	0								0
404	0	0								0
405	0	0								0
406			:1	0						:1
407			:1	0						:1
408			:1	0						:1
409			:1	0						:1
410			:1	0						:1
411					0	:1	0			:1
412					0	:1	0			:1
413					0	:1	0			:1
414					0	:1	0			:1
415					0	:1	0			:1
416					0	0	0			0
417								:1	:1	:2
418								:1	:1	:2
419								:1	:1	:2
420								0	0	0
	0	0	:5	0	0	:5	0	:3	:3	

Figure 16-21: Comparison Matrix for the Fluidics Separator



	CE02	CE01	CE05	CE06	CE04	CE03	CE07	CE08	CE09	
501	0	0								0
502	0	0								0
503	0	0								0
504	0	0								0
505	0	0								0
506			0	0						0
507			0	0						0
508			0	0						0
509			0	0						0
510			0	0						0
511					0	:1	0			:1
512					0	:1	0			:1
513					0	:1	0			:1
514					0	:1	0			:1
515					0	:1	0			:1
516					0	0	0			0
517								:1	:1	:2
518								0	0	0
519								0	0	0
520								0	0	0
	0	0	0	0	0	:5	0	:1	:1	

Figure 16-22: Comparison Matrix for the Micro Pump



	CE02	CE01	CE05	CE06	CE04	CE03	CE07	CE08	CE09	
601	0	0								0
602	0	0								0
603	1	0								1
604	1	0								1
605	1	0								1
606	:1	0								:1
607	0	0								0
608			0	0						0
609			0	0						0
610			0	0						0
611			1	0						1
612			:1	0						:1
613			0	0						0
614			0	0						0
615					0	0	0			0
616					0	0	0			0
617					0	0	0			0
618					0	0	0			0
619					0	0	0			0
620					0	1	0			1
621					0	:1	0			:1
622					0	0	0			0
623								:1	:1	:2
624								0	0	0
625								0	0	0
626								0	0	0
627								0	0	0
628								0	0	0
	3:1	0	1:1	0	0	1;1	0	:1	:1	

Figure 16-23: Comparison Matrix for the Acoustic Amplifier

17 Appendix G: Descriptions of the Test Case Equipment

17.1 Equipment

17.1.1 Klocke Nanotechnik

The Klocke Nanotechnik (shown in Figure 17-1) consists of four linear stages and a gripper, supported by a vision system and zero-heat light source. The linear stages have a range of 50 mm and a resolution of 2 nm. This is achieved through the implementation of piezoelectric stepper motors and the ‘stick-slip’ principle. This enables highly repeatable motion over a large distance. The Klocke was selected for its very high resolution and repeatability as well as its stability for long periods without motion. This stability is an essential feature in ensuring that the adhesive cures with the two parts in exactly the right location.

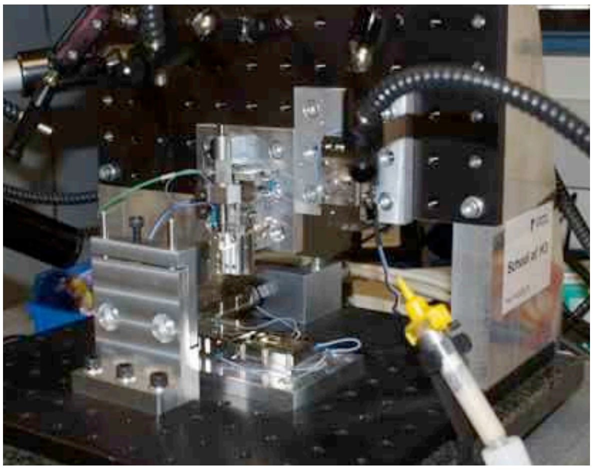


Figure 17-1: The Klocke Nano Precision Assembly Station

17.1.2 Zeiss NVision 40 FIB/SEM

The Zeiss NVision (shown in Figure 17-2) is capable of performing several different tasks simultaneously upon samples held in its vacuum chamber (shown in Figure 17-3). These include SEM, FIB, Gas Injection System (GIS), and manipulation via two Kleindiek nano resolution manipulators. These functions have been further enhanced with the additional functionality of the shuttle module, which is used to transfer samples into and out of the chamber through the airlock. The SEM beam offers imaging with high resolution at magnifications in excess of 300 000×. The FIB is able to machine samples at scales ranging from 10 nm to 10 000 nm. The functionality of the FIB is enhanced by the GIS, which can deliver several materials to be deposited onto the sample with the same resolution. The integrated manipulators have a resolution of 1 nm and are controllable in four degrees of freedom. They have modular tooling, enabling rapid changes of end effectors for different functions. These systems form the basis for the proposed solutions and the experimental work undertaken.

Figure 17-2: The Zeiss NVision 40 FIB/SEM Crossbeam

Figure 17-3: The vacuum chamber of the Zeiss NVision

17.1.3 Zeiss F25 CMM

The second stage of evaluation utilised a Micro Coordinate Measuring Machines (CMMs). The measurement and quantification of features and products from the microscale and precision manufacturing industries often requires uncertainties and resolution in the nanometre range. The best means of delivering these requirements is through high accuracy CMMs [Stoyanov et al, 2008]. An example of such a machine is the Zeiss F25, shown in Figure 17-4. The F25 has a quoted volumetric accuracy of 250nm. Work at the Precision Manufacturing Centre (PMC) has suggested that the F25 is more accurate than claimed by Zeiss [Smale et al, 2009]. The Zeiss F25 was used to determine the thickness of individual discs prior to joining. It was also used to measure the thickness of the completed assemblies post-joining. This detailed evaluation was conducted in order to "pair-up" discs with a confirmed total thickness. Each pair was stored and labelled so that, post joining, the measurement data could be accurately interpreted.

Figure 17-4: Image of the Zeiss F25

17.1.4 Ultrasonic Welding and Equipment

The Ultrasonic Welding (USW) process is a method of joining two parts through conversion of electrical energy into heat energy [Daniels, 1965]. High frequency mechanical vibrations, combined with pressure, induce melting and thus join two parts together [Hazlett and Ambekar, 1970]. USW is suitable for joining of both plastics and (non-ferrous) metals [Joshi, 1971]. The technique has been used industrially since the 1950's, [Brodyanski, et al, 2005] but this has been at the macro scale. USW is a useful joining technique because of the low temperature, high yield rate and flexibility of the process [Devine, J., 2001] and [Elangovan, et al, 2009]. The key advantages of ultrasonic welding include; low energy consumption, ability to join dis-similar materials and low operational temperatures [Harman, 1997] which allows for the potential to embed electronics and to use the process with delicate parts. Furthermore, USW is environmental friendly and very fast [Dushkes, 1973], [Hu, et al, 1991] and [Mayer and Schwizer, 2002]. An additional benefit is that the welds are produced without consumables, such as solder or adhesives, which are a feature of conventional joining processes [Siddiq and Ghassemieh, 2008]. The mechanism upon which USW is based has been investigated for several decades, but remains to be fully understood [Tucker, 2002]. This is particularly the case within the application of USW to the micro world; whilst there have been some efforts in joining of parts with micro features [Truckenmuller et al, 2006], there has been little quantitative understanding or investigation into feature design at the micro scale.

The USW process utilises ultrasonic vibrations in the vertical axis to stimulate a part into motion. This motion causes friction between the two parts, which generates heat and causes the contact area between the parts to melt. When the vibrations are stopped, the molten material freezes, joining the two parts. In the case of thermoplastics the joint is equally strong as the original material, hence the process has found use in several industries, including automotive, packaging and medical. Because molten material is created at the contact points, the vibrations cannot travel to another layer, at least not with sufficient energy to induce a second weld. This is one drawback of the process and means that each layer must be welded separately. The operation, shown in Figure 17-5 requires a number of steps:

- Two parts are stacked, one on top of the other, in a fixture beneath the welding head (horn).
- The horn descends at a set speed to a predefined contact point. This point is preset and is the height at which contact should be made with the part. If no contact is made within a small window either side of that point, the operation is aborted.
- Once at the contact point, the horn then applies a small compressing force over a set distance. This is used to ensure that the parts are fully in contact and to minimise lateral motion during welding. This is followed by a dwell period to stabilise the parts.

- The welding process is initiated and continues until one of three trigger points is reached: weld distance, weld time or energy. As soon as the first of these is reached, the welding stops and the horn retracts.

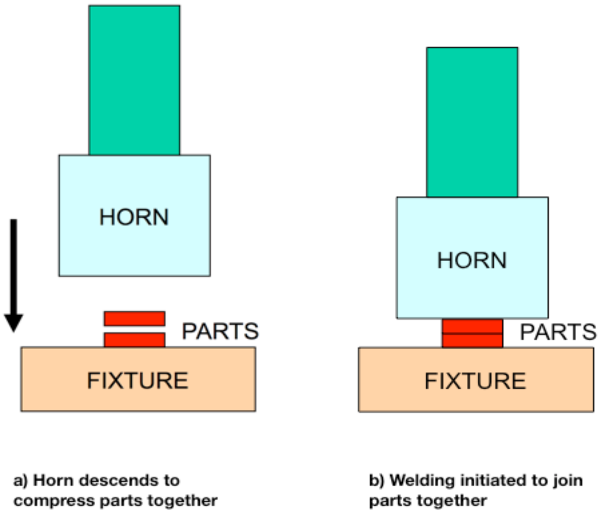


Figure 17-5: Representation of the USW process

Because the USW process relies on the contact between two parts, it is generally preferable to have control over the contact area. This is known as an energy director, as it focuses the energy from the welding horn to a specific location within the joint. There are a number of different standard joints and connections, which are described and investigated by [Suresh and Roopa Rani, 2007]. The conventional approach is to use press-fit connections, where one part is pressed into the other. This removes the need for an energy director, as the joint is required across the entire area where the surfaces meet. Upon welding, the parts are pressed together further and the sidewalls are welded: this provides an excellent and controllable joint. This is not feasible for this test case. Instead, two flat faces must be joined. Further complications associated with this test case are the scale and the tolerances; neither of which are common to the USW process.

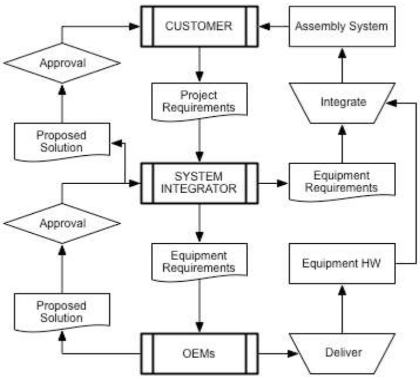


Figure 17-6: Image of the Sonics and Materials Electro Press

USW requires highly specialised equipment; typical vibration frequencies are in the range of 20-40kHz. The amplitude varies with the nature of the application, but will be in the range of 40-90μm. The PMC currently has one suitable piece of equipment: the Sonics & Materials' 40 kHz ElectroPress (shown in Figure 17-6). The unit is highly precise and controllable, both in terms of the motion of the press and the welding process itself. Vibrations with frequency of 40kHz and 40μm amplitude are suited to smaller products and features. The press uses an electric stepper motor, with optical linear encoder, to deliver precise vertical motion. This is supported by control of the vibration generator. Control of several key factors is available, these being: Weld depth, weld time, weld power and energy dissipated. Combined, this delivers a weld depth tolerance of ±8μm. Whilst this is a good capability, it is close to the maximum permissible gap between the layers. Therefore, process control and feature design become highly important.

18 Appendix H: Details of the Microdevice Assembly Trials

18.1.1 Microdevice 1 – The Micro Probe

The measurement and quantification of features and products from the microscale and precision manufacturing industries often requires uncertainties and resolution in the nanometre range. The best means of delivering these requirements is through a high accuracy Coordinate Measuring Machine (CMM) [Stoyanov et al, 2008]. CMMs are instruments that utilise a combination of physical contact between the subject part and the probe and optical feature recognition to provide accurate geometrical data. However, the current state-of-the-art CMMs are often restricted by the relatively large and insensitive probes used. An example of such a machine is the Zeiss F25.

18.1.1.1 Micro Probe Design

The micro-CMM probe presented here was developed at NPL to help realise the accuracy and traceability required by the microscale and precision manufacturing industries [Haitjema, Pril and Schellekens, 2001].

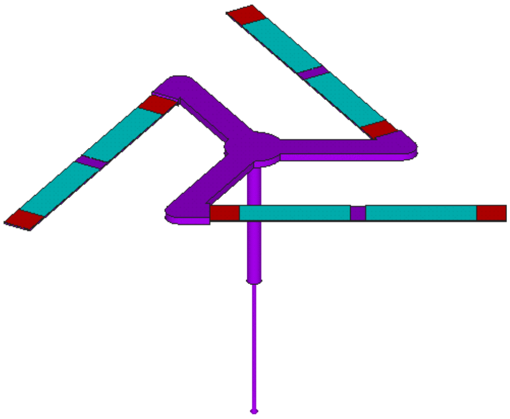


Figure 18-1: Image of the micro CMM probe, designed by NPL

The probe is comprised of a solid shaft, a flexure assembly, and a probing sphere. A 3D model of the device is shown in Figure 18-1. The shaft is manufactured from tungsten carbide (WC) via EDM and wire eroding. The flexure assembly is a laminar structure, manufactured by a micromachining process. The flexures include PZT actuators and sensors that are deposited onto the surface of the structure during the manufacturing process. The probing sphere attached to the end of the WC shaft is made of silica. The shaft is 200 μm in diameter where it joins the flexure and 70 μm in diameter where it joins the probing sphere. The shaft is connected at the thick end to the delicate piezoelectric flexure structure via a 100 μm diameter spigot. At the thin end a 100 μm diameter glass sphere is connected concentrically. These joints must be made without damaging any of the components, but special attention is placed on the protection of the sphere. The assembly requirements for the shaft onto the flexure specify a positional accuracy of ± 0.5 μm and the angle between the shaft and flexure to be 90° ± 0.29°. These factors are of primary importance in ensuring correct function of the final product.

18.1.1.2 Methodology

The overall approach within this element of the research is that the product design be evaluated with respect to the specific assembly and performance requirements. From this, potential solutions were generated and a number selected for testing. One of the primary concerns was to consider processes suitable for mass production. In the case of this product however, the anticipated volume is in the order of 1000-2000 units per year. Assuming production will be through one shift of 8 hours, five days per week, for 50 weeks per year, the required cycle time is between 1 and 2 hours. This comparatively long period allows for the consideration of processes that would normally be excluded from volume production. The first step was to evaluate the key assembly challenges posed by the Micro Probe.

18.1.1.3 Assembly Challenges

The micro-CMM probe described in Section presents a number of specific assembly challenges. These challenges result from the scale of the parts and the technical requirements of the product, detailed in Section 2.3.1.2. In order to fully evaluate the challenges and potential solutions, it was first necessary to identify the individual assembly operations. To this end, the assembly operations proposed by [Rampersad, 1994] were used to define the operations specific to this application. This was further enhanced by the use of the Design for Micro Assembly methodologies proposed by [Ratchev and Koelemeijer, 2008].

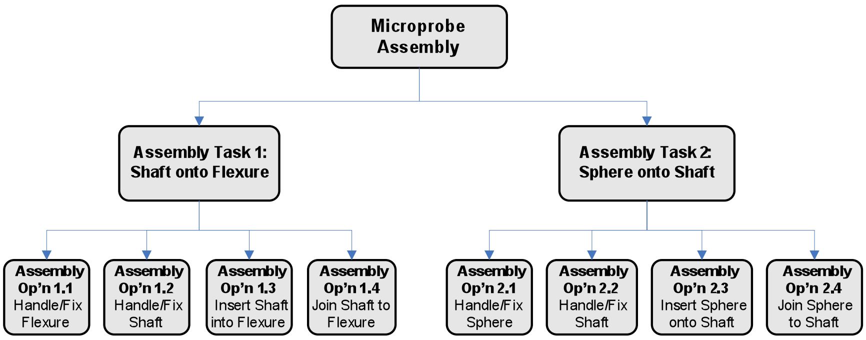


Figure 18-2: The assembly hierarchy for the microprobe

Table 18-1: Summary of the key challenges and requirements for the assembly operations of the microprobe

Assembly Operation	Challenges	Requirements
1.1 Handle/Fix Flexure	• Very thin (15 μm) flexures • Delicate structure	• Keep electrical contacts clear • Minimise stress on flexure
1.2 Handle/Fix Shaft	• Gravity no longer dominant force acting on part • WC is stiff but brittle	• Minimise acceleration and external forces • Preserve the delicate features
1.3 Insert Shaft into Flexure	• Delicate parts connecting at vulnerable point • Very restricted view	• As for 1.1 and 1.2
1.4 Join Shaft to Flexure	• Very low thermal capacity • Limited access to joint location	• Angle = 90° ± 0.29° • No distortion post-join • Joint resistant to fatigue
2.1 Handle/Fix Sphere	• Gravity no longer dominant force acting on part • Spheres unstable for gripping	• Sphericity of part is crucial • No localised damage or profile changes permissible
2.2 Handle/Fix Shaft	• Gravity no longer dominant force acting on part • WC is stiff but brittle	• Minimise acceleration and external forces • Preserve the delicate features
2.3 Insert Sphere onto Shaft	• Parts <1 mm: tension and van der Waals forces will affect alignment	• Near-perfect concentricity between sphere and shaft
2.4 Join Sphere to Shaft	• Very limited contact area • Low thermal capacity of glass prevents use of thermal processes	• No damage to parts • No joint degradation • No post-join deformation

As a result of this analysis, an assembly operation hierarchy was produced. This is shown in Figure 18-2. This hierarchy is headed by the required outcome of the process, in this case, 'Microprobe Assembly'. This outcome is broken down into two assembly tasks, numbered arbitrarily; each of these tasks is sub-divided into several assembly operations. Each of the assembly operations was analysed, with respect to the two core factors, as a means of determining the challenges faced and thus identifying a preliminary route for generating a solution. The results of this are shown in Table 18-1.

18.1.1.4 Solution Development

The solutions developed, overviewed in Table 18-2, represent a wide diversity of different methods and tools whilst others are relatively specific. The most technically demanding tasks are the two joining tasks – 1.4 and 2.4. This is due largely to the very tight constraints on positions and angles required from the complete assembly and the lack of any retaining features within the probe components. In contrast, the two insertion tasks, 1.3 and 2.3, can be achieved relatively easily. The two proposed solutions make use of the Klocke Nano Precision Assembly Station (Klocke) and the Zeiss NVision 40 FIB/SEM Crossbeam with integrated Kleindiek micro manipulators (Zeiss NVision).

Table 18-2: Overview of potential solutions to the assembly challenges for the microprobe

Assembly Operations	Potential Solutions
1.1 Handle/Fix Flexure	• A bespoke passive fixture produced to provide the necessary support and clearances.
1.2 Handle/Fix Shaft	• Use of conventional microgrippers. • Active fixture with location and retention. • Passive fixture with location and retention.
1.3 Insert Shaft into Flexure	• Use of the Klocke platform as a robotic station. • Use of the Klocke platform as an active fixture. • Use of the Zeiss NVision manipulators.
1.4 Join Shaft to Flexure	• Adhesive bonding of spigot to flexure. • Interference fit between spigot and flexure. • Precision laser welding of spigot. • Mechanical deformation of spigot post-insertion.
2.1 Handle/Fix Sphere	• State-of-the-art microgrippers. • Active fixture with location and retention. • Passive fixture with location and retention.
2.2 Handle/Fix Shaft	• Use of conventional microgrippers. • Active fixture with location and retention. • Passive fixture with location and retention.
2.3 Insert Sphere into Shaft	• Use of the Klocke platform as a robotic station. • Use of the Klocke platform as an active fixture. • Use of the Zeiss NVision manipulators.
2.4 Join Sphere to Shaft	• Adhesive bonding. • FIB substrate deposition. • Mechanical interface.

Each of the proposed solutions will impact any subsequent assembly operations. For example, by using the Zeiss NVision for the insertion task the number of available joining processes is substantially reduced due to the need for the process to occur within the vacuum chamber. It was therefore necessary to apply an iterative process for the selection of the appropriate solution.

18.1.1.4.1 Assembly Task 1 Proposed Solution

The solution proposed to deliver the assembly of the shaft onto the flexure uses the Klocke as a robotic assembly cell. The shafts are loaded onto passive fixtures, which hold the shafts in the horizontal plane, and are picked by the mechanical gripper. These fixtures support the shaft throughout the joining process, thus ensuring that the desired angle between the flexure and shaft is maintained. The flexures themselves are mounted vertically, using their fixing features, to another passive fixture which itself is mounted onto the xy motion stages. This fixture is machined such that access is available to the back of the flexure. This provides a route for the adhesive dispensing. A vision system is employed to enable the operator to guide the alignment and is coupled to a set of low-heat light sources.

18.1.1.4.2 Assembly Task 2 Proposed Solution

It was proposed that the Zeiss NVision should be used to deliver the probing sphere to the WC shaft for assembly. The shafts are loaded onto passive fixtures that hold the shafts in the horizontal plane and are connected to the transfer shuttle for use in the FIB/SEM chamber. The sphere and SEM glue are loaded onto the same fixture for transfer into the chamber. The SEM glue is deposited into a small inverted cone machined into the surface of the fixture whilst the sphere is placed onto a small quantity of carbon. Once loaded into the chamber, the SEM beam is used for imaging to guide the operator during the assembly.

18.1.1.5 Experimental Work

The constituent parts of the micro CMM probe are time consuming and costly to produce. Therefore all initial trials were carried out on replica parts. Two replica parts were produced using facilities within the PMC; the replica flexures were produced using a Kern EVO micro CNC machining station, whilst the replica shafts were produced using an EnvisionTec Perfactory Rapid Manufacturing Machine. The replica spheres are commercially mass-produced and are the correct diameter but do not have the low surface roughness that is ultimately required by the micro CMM probe. The replica parts produced were developed to mimic the behaviour of the real parts from an assembly perspective.

18.1.1.5.1 Assembly Task 1 Trials

The trials conducted initially focussed on the feasibility of the approach and only on the insertion element. These trials used a number of different interface dimensions; due to the laminar production of the real flexures, it is only possible to create a simple hole for the spigot on the shaft to be inserted into. It is not feasible to produce the substitute parts with chamfering, which is a major restriction and places emphasis on the dimensioning and tolerancing of the holes and spigots. It was decided to keep the spigot at a constant dimension (0.1 mm) and to vary the diameter of the hole in the flexure, from 0.09 mm to 0.15 mm.

The assembly trials showed the expected results - the 0.15 mm hole enabled the easiest insertion but delivered a relatively loose connection, whilst the 0.10 mm hole proved more difficult to assemble but offered a far more rigid structure afterwards. The 0.09 mm hole was too small to insert the spigot into – it was hoped that an interference fit would remove the need for the bonding process, but the delicacy of both structures meant that, even with a supportive fixture, the degree of deformation of the flexure during insertion was unacceptable.

Adhesives were tested for application on a vertical surface with repeatable drop sizes and an appropriate curing method and time frame. Selection of the correct adhesive was of paramount concern for the first trials and several different types were tested. The preferred adhesive would be rapidly curable in natural or UV light, easily dispensed, single-part, and viscous. Use of a low viscosity adhesive would fill any gaps between the connecting parts, thus ensuring the spigot does not move within the hole. However, the effect of a fluid within the laminations would be unpredictable and probably detrimental to the life span of the flexure.

The adhesive trials demonstrated that a repeatable drop could be dispensed with a diameter of 0.10 mm on a vertical surface with a number of adhesives, including NOA 68 and Loctite 3335. Curing time could be accelerated in both cases by use of a UV light source. Furthermore, these adhesives are suited to multi-material bonding and have exceptionally low shrinkage post-curing.

18.1.1.5.2 Assembly Task 2 Trials

The assembly trials using the Zeiss NVision initially focussed on the manipulation of the spheres. Two options were considered: use of a microgripper to hold the sphere between two jaws and use of a single needle tip. Whilst the gripper is preferable for its positive hold on the sphere, it is also likely to cause localised damage, at the micro- and nano-scale, to the gripped points. This kind of damage is not acceptable, as it will create indentations on the sphere that will affect the performance of the completed micro-CMM probe. Therefore, it was concluded to try to work with a single needle tip to move the sphere. This technique required a great deal of operator skill and patience to achieve. A view of the assembly process is shown in Figure 18-3. The procedure followed to facilitate assembly is as follows: (1) Locate the sphere on the fixture and bring the needle tip to it. (2) Carefully push the sphere horizontally across the fixture surface to weaken the tension forces between the carbon and the sphere bond. (3) At a critical point, the tension forces between the sphere and needle exceed that of the sphere and the carbon and the sphere then becomes attached to the needle. (4) Manoeuvre the sphere to the end of the shaft for joining.

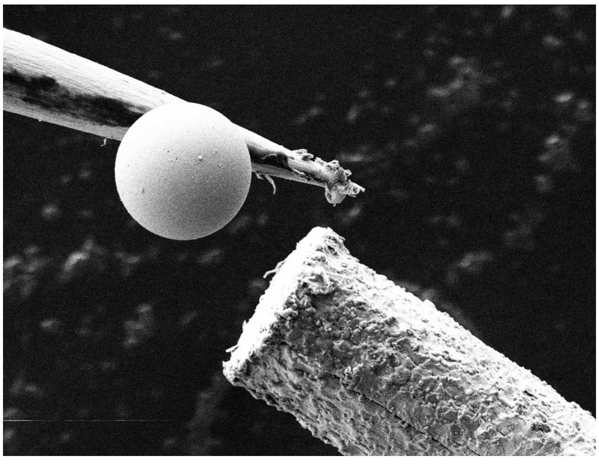


Figure 18-3: SEM image showing the assembly of the sphere onto the shaft

This process does leave some residual adhesive on the surface of the sphere, however this should be easily removable with a non-abrasive cleaner. With the sphere in place, the next trials focussed on joining the sphere to the shaft. The two main processes available were the use of a SEM-specific adhesive or the use of a FIB to deposit carbon tabs connecting the two parts. Since the adhesive would have to be manually applied to the shaft with the second manipulator, it was decided to test the feasibility of the FIB deposited tabs first. However, a number of factors adversely affect the potential success of such an approach. Firstly, FIB deposition is intended to be used at the sub-micrometre level and so producing tabs large enough to bridge the two parts in question would take in excess of twelve hours each. Secondly, as with all tab welds, it is necessary to hold both parts together and apply tabs from all sides – this is simply not possible within the vacuum chamber of the Zeiss NVision. Thus it became necessary to investigate the potential use of an SEM glue. These adhesives are sufficiently viscous so as not to evaporate when placed in a vacuum chamber and are cured by a SEM beam. However, this also poses a significant challenge in giving limited time to complete the assembly as the SEM is used for viewing and guiding the process. As of yet the PMC has not achieved a sufficiently strong bond for the complete assembly to survive the rigours of the re-pressurisation process. However the feasibility of such an approach has been demonstrated.

18.1.2 Microdevice 2 – Microfluidics

The product is a microfluidics device consisting of several discs stacked on top of one another. The discs are 10mm in diameter and 1mm thick. They are manufactured through a micro-injection moulding process from a suitable polymer; Polymethyl methacrylate (PMMA). PMMA is a transparent thermoplastic, used frequently in place of glass; it is selected due to the ease of processing both in moulding and in ultrasonic welding. Furthermore, the transparency enables the path of a (coloured) fluid to be inspected without the need for destructive testing.

18.1.2.1 Methodology

The overall approach within this element of the research is that the product design be evaluated with respect to the specific assembly and performance requirements. From this, potential solutions were generated and one selected for testing.

One of the primary concerns was to consider processes suitable for mass production. In the case of this product, the anticipated volume is in the order of in excess of 500,000 units per year. Assuming production will be through one shift of 8 hours, five days per week, for 50 weeks per year, the required cycle time is approximately 15 seconds.

18.1.2.2 Assembly Challenges

Whilst the discs are relatively large, the gap *between the layers* must not exceed 20µm as each disc contains a number of micro channels which cross the boundary between the layers. Simulations have demonstrated that a gap of less than 20µm will result in little of the fluid entering the gap and thus will have a negligible effect on the performance of the device. There are a number of specific requirements at this stage, which are summarised in Table 18-3.

Table 18-3: Summary of the key challenges and requirements for the assembly operations of the microfluidics device

Assembly Operation	Challenges	Requirements
1.1 Handle/Fix Disc	• Retain only by side walls	• Keep fluidics features clear • No rotational alignment is necessary • Parts must be retained in position during joining
1.2 Insert Disc into Fixture	• Fixture for tall assembly of parts, restriction of access	• Positional tolerances are ±20µm • Assembly is 5 components high
2.1 Handle/Fix Disc	• As for 1.1	• As for 1.1
2.2 Locate Disc A onto Disc B	• As for 1.2	• As for 1.2
2.3 Join Disc A to Disc B	• Maintaining required geometries and dimensions • Prevention of contamination of fluidic channels	• Excellent sealing • Excellent parallelism • Fast and clean operation

The Handling processes do not present any specific requirements – the component parts are relatively large and robust and conventional technologies are fully applicable. Because the five components are, from an assembly perspective, identical, achieving this joint is the only operation and is performed four times.

18.1.2.3 Solution Development

The major focus of the research effort is in achieving the required joint. As indicated in Table 18-4, the majority of the defined Assembly Operations can be addressed by conventional equipment and processes.

Table 18-4: Overview of potential solutions to the assembly challenges of the microfluidics device

Assembly Operations	Potential Solutions
1.1 Handle/Fix Disc	• Conventional mechanical gripper. • Conventional vacuum gripper.
1.2 Insert Disc into Fixture	• Conventional robotics. • Conventional linear actuators.
2.1 Handle/Fix Disc	• As for 1.1
2.2 Locate Disc A onto Disc B	• As for 1.2
2.3 Join Disc A to Disc B	• Adhesive bonding. • Mechanical clamping. • Plastic welding.

Of the three potential solutions to Assembly Operation 2.3, adhesive bonding and mechanical clamping have been trialled during early prototyping phases and demonstrated to be unsuitable. Thus the remaining solution was to consider plastic welding.

18.1.2.3.1 Plastic Welding Options

The welding of plastics is a common process and is facilitated by the low melting point of the majority of polymers, including PMMA (melting point = 160°C). This leads to a large variety of heat-based processes, including: hot gas welding, speed tip welding, extrusion welding, contact welding, hot plate welding and high frequency welding. However, these processes have a number of drawbacks for application to microdevices. They are generally applied at the macro scale, and so lack the fine control of position. Further, they typically require the application of a medium plastic for bonding, which reduces the accuracy of location and particularly the repeatability of thickness.

There are however a number of processes that, whilst ultimately inducing welds through the melting of the polymer, do so with a much higher degree of control. These are:

- Solvent welding
- Laser welding
- Friction welding, including Spin welding
- Ultrasonic welding

Solvent Welding is a similar process to adhesive bonding – however the low viscosity of the solvent further complicates the application, which risks contaminating the fluidic features. *Laser Welding* of plastics is also complex and requires a high degree of control of the beam, as well as the ability to focus the weld at the location required. This typically requires a change in material properties, which is not the case in this joint. *Friction Welding* uses low frequency, high amplitude motion between parts to generate heat and bond two parts. By its nature, this is not a typically accurate process. *Ultrasonic Welding* (USW) offers the potential to create bonds through localised heating. This is induced by high frequency, low amplitude relative motion between parts. This makes it the most suitable approach for precision joining. The details of the USW process and the equipment are provided in Appendix F.

18.1.2.3.2 Design Modification

A critical step in the application of the USW process was to design a suitable joining feature. It is not desirable to rely on random surface interactions and contact points to provide the welding zones. This would be unpredictable and result in highly variable welds being produced. It was therefore decided to design an appropriate energy director feature and evaluate the performance of the welds produced.

An important consideration during the feature design was the manufacturing of the discs themselves: the parts are produced on a micro injection moulding machine, using a two-part modular mould. The impact of this is that new features can be machined into the modular and replaceable parts of the mould and production trialled without the need to produce an entire new mould. This is a time and cost efficient means of investigating multiple options. However, the drawback is that features can only be produced on one side of the discs. This has a substantial impact on the design of the joining feature. Typically, the joint feature for a flat-face joint would exist on both sides of the join. The energy director would have a height of approximately 0.1mm and be flanked by flash traps to catch any molten material.

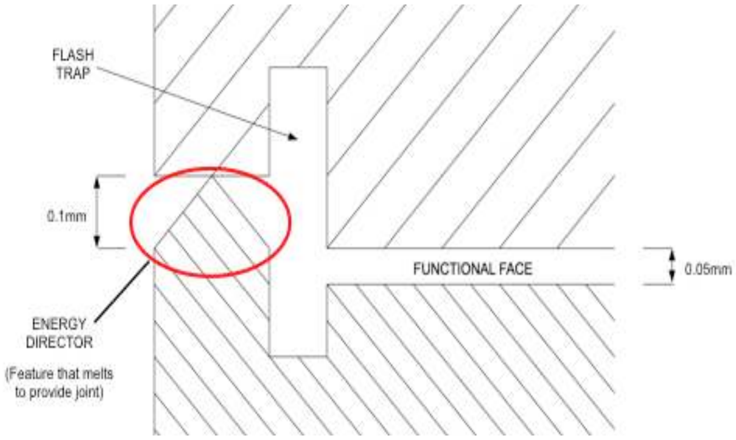


Figure 18-4: Preliminary design of the joint feature

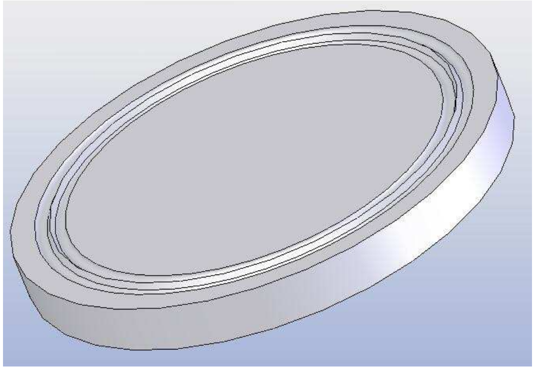


Figure 18-5: Image of the CAD model used to produce the discs with single side joint feature

An initial design of such a feature, suitable for this application, is shown in Figure 18-4. The feature uses an energy director on the outermost point of the disc. Thus only one flash trap is required and the joint is kept as far from the fluidics features as possible. Furthermore, the height of the joint is deliberately different from the height of the mating faces. This is designed to prevent molten material from being ‘injected’ into the gap by the compression of the parts during welding. However, due to the restriction in production, in this research it is necessary to design a single-sided joining feature. The design produced was adapted from the preliminary feature design, with specific consideration of the potential manufacturing process. The full CAD model used to produce the parts is shown in Figure 18-5. The feature designed is a ring with a diameter of 9.0mm; the section of the ring is 0.50mm across and 0.2mm tall. The feature consists of a single peak, which stands proud of the surface by 0.05mm. This provides the contact point between the two parts, which is flanked by two flash traps. These have been deliberately made to be relatively large so as to ensure that no material enters the gap between the two surfaces and to account for the joint height being the same as the mating faces. Figure 18-6 shows a Scanning Electron Microscope (SEM) image of the produced feature. The image also shows part of the fluidics feature, in this case one of the reservoirs. The major outcome of this research is to evaluate the degree of success and the viability of this substantially simplified joint design.

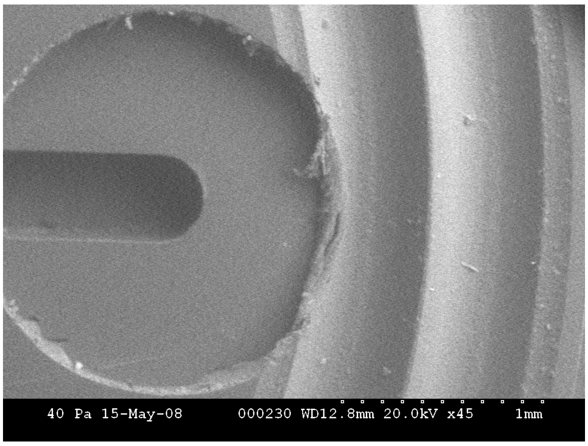


Figure 18-6: Image from SEM of produced disc with single side joint feature and microfluidics reservoir

18.1.2.4 Measurement and Verification

The ultimate objective of the processing is to deliver a stack of discs with a total height not exceeding that of the sum of the thicknesses of the discs. Controlled and reliable production of the discs has already been largely achieved; the target thickness (the most critical dimension for this research) of 1.00mm ±10μm is achieved in approximately 90% of parts. This data is based upon 100% measurement of a large sample set. At each stage of experimental research, the discs are measured and only those with thickness of 1.00mm ±10μm are accepted and used for experiments. However, this deviation still represents a substantial proportion of the allowable gap between the layers. It is therefore essential that the dimensions of the parts, specifically the thickness, be fully quantified before and after joining to accurately assess the level of success of the weld.

The measurement of the thickness of the discs prior to joining was accomplished through the implementation of a number of strategies. Firstly, Digital Micrometers (calibrated using ISO 9001 standards) were used to measure all of the produced discs and to detect parts with large variations (greater than 10µm) from the target dimension. Those that had an indicated thickness of between 0.99mm and 1.01mm (1.00±0.01mm) were placed into a group for the second stage of evaluation. The remaining discs were rejected or used for other testing.

The second stage of evaluation utilised a Zeiss F25 CMM (described in Appendix F). The Zeiss F25 was used to determine the thickness of individual discs prior to joining. It was also used to measure the thickness of the completed assemblies post-joining. This detailed evaluation was conducted in order to “pair-up” discs with a confirmed total thickness. Each pair was stored and labelled so that, post joining, the measurement data could be accurately interpreted.

Post joining, the samples were first visually inspected using and optical microscope and an SEM. After visual inspection the same metrology process was applied as to the individual discs: Digital Micrometers were used to give an approximate dimension, then the Zeiss F25 was used to give a precise overall height. This was compared to the original disc dimensions and the target product height.

18.1.2.5 Summary of Trials

During the testing phase, a large number of parts were used to establish the welding parameters. Due to the size and scale of the joint features, very low time, distance and energy settings were used. The values were initially set to the minimum deliverable by the equipment (0.01s, 0.02mm and 0.05J respectively). These values proved to be insufficient to induce welding so the parameters were increased. After several iterations, successful welding was achieved with high repeatability. Some of the samples were visually inspected as described previously; the images (an example is shown in Figure 18-7) demonstrated that a large and inconsistent gap existed between the discs.

The joining process was thus further refined through several iterations of variation of welding parameters, trials and inspection. After numerous attempts, parts were produced without a visible gap between the layers. An example image is shown in Figure 18-8, this image also shows that molten material has been expelled from the joint to the outside (demonstrated by the small piece of material stuck to it). This indicated that either the flash trap had not performed it’s purpose or that secondary welding had occurred at the perimeter of the discs. Measurement of the joint discs indicated that the gap between them was less than 10µm, which would be an excellent result, assuming that any secondary welding had not blocked the microfluidics channels.

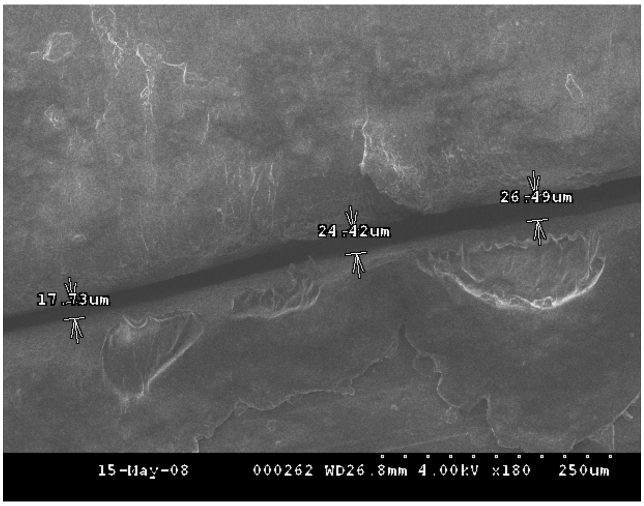


Figure 18-7: SEM image of a joined produced showing the inconsistent gap between the layers

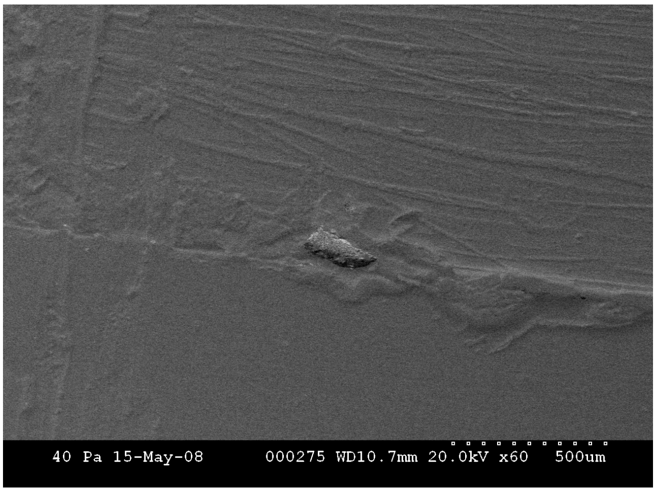


Figure 18-8: SEM image of a joined product showing the fused layers and expelled flash to which material has stuck

Thus, further to this Non Destructive Testing (NDT), it was decided to perform Destructive Testing. This involved sectioning of joined parts to visually inspect the joint. This was performed using a Kern Evo micro-milling machine with a 0.15mm end mill tool. The parts were fixtured into the machine and slowly cut through the middle to a depth of 1.5mm. This depth ensured that the joint was sectioned, but that the parts remained joined and within the fixture. The parts were then cleaned and imaged. An example image is shown in Figure 18-9, which also shows that the flash trap was largely unfilled and thus substantially bigger than necessary. The images also revealed that secondary welding had occurred either side of the flash trap feature but that this had not extended into the fluidics features.

This conclusion was confirmed by injecting coloured water into the parts – the fluid followed the expected path and did not demonstrate any blockages. Subsequently, all of the joined samples where measured according to the previously defined strategy. The results from this measurement effort are shown in Table 18-5.

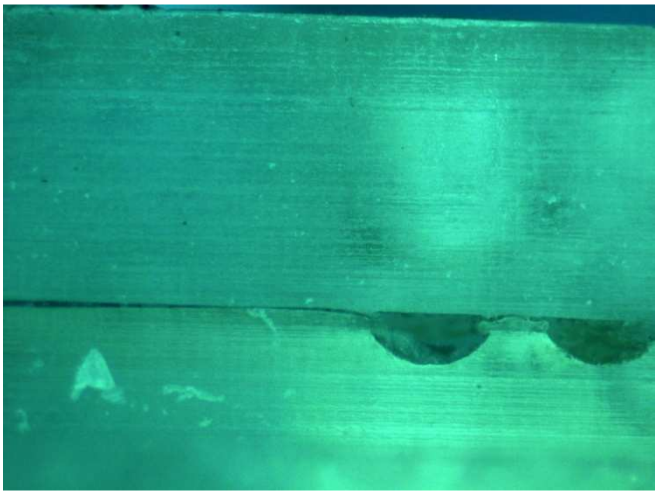


Figure 18-9: Image of section product showing the joint and flash trap

Table 18-5: Summary of joining results from refined USW processing

Thickness difference*	Within tolerance?	% of parts
negative µm	Y	0
0-5 µm	Y	24
6-10 µm	Y	44
11-20 µm	Y	16
20+ µm	N	16
* Calculated by subtracting the sum of the two thickness values for the separate discs from the thickness of the completed assembly		