THESIS FOR THE DEGREE OF LICENTIATE OF ENGINEERING

# FLEXIBLE FIXTURES – A TREATISE ON FIXTURE DESIGN AND EFFICIENCY

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Flexible Fixtures – A Treatise on Fixture Design and Efficiency
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Cover: Holon of Seven Criteria of Flexible Fixtures

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# ABSTRACT

Even though a variety of efforts have been made in the area of flexible fixtures, the manufacturing industry still relies on dedicated fixtures with minor modular features. The main underlying reason, as these attempts have shown, is that the application of flexible fixtures has failed to yield the expected results, with the implemented technologies often leading to increased manufacturing costs when compared to dedicated fixtures. As this has a negative impact on industry's return on investment, a grey and largely uncharted area has arisen around the efficiency of flexible fixtures. The research that forms the basis of this thesis is intended to identify, describe and increase the efficiency of flexible fixtures in manufacturing industry. In order to fulfil this aim, two research questions have been asked. The first question focuses on exploring and description of the efficiency, while the second question focuses on how methodically the concept of efficiency can be used in fixture design.

The results presented in this thesis are based on four experimental studies carried out in the automotive and aerospace industries covering different aspects of modular and reconfigurable fixtures with manual, automated and active features. Based on these experimental studies, seven criteria regarding the efficiency of flexible fixtures have been identified. These criteria relate to *physical flexibility*, *quality*, *interactivity*, *cost*, *time*, *modularity* and *maintenance*. Furthermore, the thesis provides the expected states of criteria along with relevant metrics. Subsequently, a design procedure using these metrics is presented based on the characteristics of a manufacturing system, in order to identify the most efficient fixturing solution. Finally, the efficiency of flexible fixtures is found to be correlated to the individual and unique needs of a manufacturing system. Consequently, the ability of a fixture designer to understand and adapt to those needs is the key to increased efficiency; thus, the applicability of flexible fixtures.

**Keywords**: Flexible, reconfigurable, fixture, tooling, efficiency, design.

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# APPENDED PUBLICATIONS

**PUBLICATION A**

I. Erdem, H. Kihlman, and A. Andersson, "Development of Affordable Reconfigurable Tooling in Car Manufacturing Cells – A Case Study," in *ICPR23 International Conference on Production Research*, 2015.

**PUBLICATION B**

I. Erdem, P. Helgosson, and H. Kihlman, "Development of Automated Flexible Tooling as Enabler in Wing Box Assembly," in *Procedia CIRP*, 2016, pp. 233-238.

**PUBLICATION C**

I. Erdem, P. Helgosson, A. Gomes, and M. Engstrom, "Automated Flexible Tooling for Wing Box Assembly: Hexapod Development Study," in *SAE Technical Paper 2016-01-2110*, 2016.

**PUBLICATION D**

I. Erdem, C. Levandowski, C. Berlin, H. Kihlman, J. Stahre, "A Novel Comparative Design Procedure for Reconfigurable Assembly Fixtures," *CIRP Journal of manufacturing Science and Technology*. *(Submitted)*

*Work Distribution: All publications were initiated and largely written by Ilker Erdem. The remaining authors contributed to the body of knowledge and by reviewing the work.*

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# LIST OF ABBREVIATIONS

| | |
|---|---|
| AMS | Agile Manufacturing Systems |
| AProC | Automated Process Control BiW |
| ART | Affordable Reconfigurable Tooling |
| BiW | Body-in-White |
| CAFD | Computer Aided Fixture Design |
| CAPP | Computer Aided Process Planning |
| CIMS | Computer Integrated Manufacturing System |
| DOF | Degrees of Freedom |
| DRM | Design Research Methodology |
| FMS | Flexible Manufacturing Systems |
| LOCOMACHS | Low Cost Manufacturing and Assembly of Composite and Hybrid Structures |
| MachOpt | Machine Optimization Learning |
| MPS | Modular Production Systems |
| MTC | Manufacturing Technology Centre |
| GT | Group Technology |
| PKM | Parallel Kinematic Machine |
| PLC | Programmable Logic Controller |
| PMS | Performance Measurement Systems |
| RMS | Reconfigurable Manufacturing Systems |
| RQ | Research Question |
| SMED | Single Minute Exchange of Die(s) |

# I

# INTRODUCTION

With the increasing demand for responsive manufacturing systems, a certain amount of research has been carried out to explore the dynamics of different elements in a production system. Within this broad research, various definitions and models have been built to identify and allocate characteristics to different production elements. Manufacturing technologies as constituents of production have been an integral part of this dynamic relationship, interacting not only internally but also externally with other elements of a production system. Fixtures, being one of these manufacturing technologies, have played a role in building this relationship. This chapter aims to identify these dynamics from a fixture perspective and introduces the formulation of the fundamental research components of the thesis – its aim and research questions.

## 1.1 FIXTURING IN MANUFACTURING AND PRODUCTION SYSTEMS

Even though multiple definitions clarifying the hierarchical distinction between a manufacturing and production system exist, the apex of the hierarchy can be defined as the systematic activities of products and services that span from designing and procuring to aftersales services. If these activities are reclassified as subsystems, then a particular physical subsystem that involves planning, control and product realisation processes becomes a centre of attention [1]. Within this hierarchical approach, the first definition accepts a manufacturing system as the crown of the chain whereas a mirrored definition considering the production system as the hierarchically outranking also exists [2].

Regardless of the difference in the definitions proposed, the terminology utilized by this thesis in terms of activity classification takes manufacturing systems as the acme in the hierarchy. This classification includes various approaches spanning from mass production to cyber-physical manufacturing systems where, in each, the production system concept is treated as a physical system. Based on this approach, further definitions are essential in order to build a foundation to distinguish between different terms. Thus, the physical system is broken down into different manufacturing processes where the term *manufacturing process* defines a method to create a feature on a product. Moreover, the equipment or resources used to realise this method are defined as *manufacturing technologies*. Within manufacturing processes, manufacturing technologies represent the system of resources and equipment utilized to add a feature to a product or workpiece. The resources and equipment denote only the group of items dedicated to a certain process; meaning that material handling within a process or other processes is not included. The resources are within the spectrum spanning from humans to fully automated machinery, whereas equipment symbolises all supporting items such as tooling and manual tools. The concept of manufacturing and production systems along with the constituents of the manufacturing hierarchy is illustrated in figure 1.

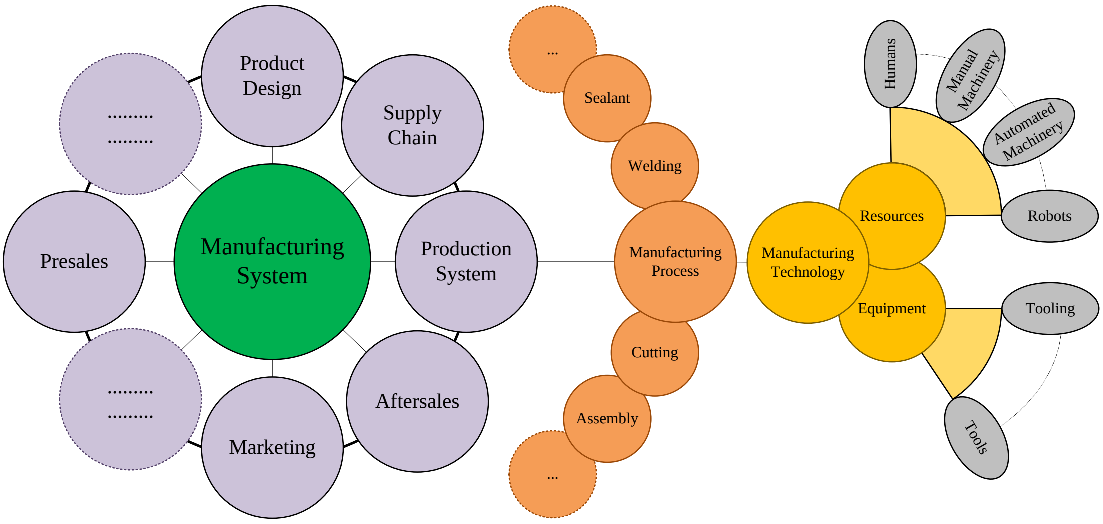



Figure 1. Manufacturing hierarchy and the concepts of manufacturing and production systems

The final classification that establishes the position of fixtures within the hierarchy lies in the terminology of tooling. A tooling group is a composition of two different functionalities. The first functionality represents the interaction between the workpiece and the resource. Machining and assembly applications; and cutting tools and cutting support components, or jigs, are two examples of this interaction. The second functionality is based on securing the workpiece in a certain position and orientation, known as workpiece holding. The latter functionality, and the devices belonging to that family, are designated as fixturing and fixtures respectively [3].

Another important point in the exploration of fixtures and their interacting dynamics is to understand and correlate them to changes in the higher classes of the hierarchy. In the chronological development of manufacturing paradigms, the impact of different philosophies required production systems and their subgroups to evolve. In this adaptation process, the subgroups of a production system are triggered to reshape their functionalities in order to execute their tasks in accordance to the requirements of the emerging manufacturing philosophy. An example of this can be seen in the formulation of *emergent synthesis based manufacturing paradigms*, where each philosophy formulates a set of requirements on the behaviour and functionalities of every element in a production system [4]. When these requirements are embodied in the corresponding manufacturing technology, the fitness of the evolution is analysed –initialising a selection process. Consequently, the dynamics of the hierarchy becomes complete as the performance of the new functionalities are perpetually evaluated based on an input-output relationship in the chain-of-manufacturing hierarchy.

A classic, yet fundamental, example of the aforementioned dynamics is the introduction of flexibility in manufacturing systems. When the pressure for responsiveness became evident, pushing manufacturing systems to become more than a mass-production environment, a new paradigm was formulated. In this paradigm, the constituents of a manufacturing system were required to adapt rapidly in a cost-effective manner [5]. Within these requirements, the concept of flexibility was introduced into production systems through parameters where each subcomponent and its systematic working structure is reshaped and evaluated. Later, the concept developed into a manufacturing philosophy known as Flexible Manufacturing Systems (FMS) [6]. Besides the apparent change in manufacturing resources, an impact of magnitude was also evident in the evolution of fixtures. With the emphasis on flexibility, a new and corresponding fixturing paradigm was established relying on the assembly of modular components to construct fixtures. These fixtures – which later came to be known as *modular fixtures* and provided the first examples of flexible fixtures – were widely implemented, particularly in the automotive and aerospace industries [7, 8]. Later, the evaluation phase was initiated by measuring the manufacturing paradigm parameters [9]. Accordingly, the dynamics between FMS and its elements in the hierarchy were formed from a manufacturing paradigm perspective.

As described, the dynamic relationship between the manufacturing and fixturing paradigms is hierarchical; thus, each shift in a manufacturing paradigm triggers a change in the fixtures. Within this organic relationship, the phases of designing, deploying and evaluating were methodized and numerous design-to-deploy processes were created [10, 11]. However, with new manufacturing paradigms, the set of requirements on fixtures started to evolve. An example of such an evolution can be observed with the introduction of Reconfigurable Manufacturing Systems (RMS). The impact of RMS shaped the fixture's nature from modular to reconfigurable, with numerous researchers attempting to find an optimized fixturing solution. For the aerospace industry, one of the proposed solutions was the utilization of external automation resources such as an articulated robot to reconfigure parallel kinematic devices [8, 12-14]. When attempts were made to implement the RMS philosophy in the automobile industry, the resulting fixtures were internally automated [15, 16]. Consequently, each emerging manufacturing paradigm provides the basis of a new fixturing technology in terms of requirements, whereas each requirement has a corresponding result. Thus, the relationship between requirements and results establishes performance criteria for fixtures – or, in other words, fixturing efficiency.

## 1.2 STATING THE GREY

Even though the dynamics between paradigm shifts and manufacturing technologies can be well described from a chronological perspective, the versatility of manufacturing paradigms and flexible fixturing solutions create a considerable niche. Within this niche, the established modular fixtures and FMS remain unique in terms of application, as the majority of manufacturing industries still utilize modular and dedicated fixtures. This particular situation indicates an uncharted territory for the remaining flexible fixtures. Furthermore, recent academic publications and reviews of the available technologies reach a common conclusion in that the majority of the industries in this niche suffer from cost and time-related perspectives [17, 18]. This indicates that a certain number of flexible fixtures remain in a nebulous zone where the dynamics between corresponding manufacturing paradigms and the fixturing solutions created might be correlated to inefficiency and methodical development.

## 1.3 AIM AND RESEARCH QUESTIONS

Based on the formulation above, the aim of this research is to increase the efficiency of flexible fixturing solutions in manufacturing industry. Therefore, the first research question is formulated as following

*RQ 1)* What are the criteria that can be used to describe the efficiency of flexible fixtures?

In order to answer *RQ 1*, an analysis must be made of what constitutes flexible fixture efficiency. Consequently, this question establishes a basis to achieve this as well as providing results that can be used as input to the second question; articulated as

*RQ 2)* How can these criteria be methodically used in the design of flexible fixturing solutions to increase their efficiency?

The response to which will attempt to include the criteria in a methodical and repeatable manner. The methodical approach will structure the design of flexible fixtures so that the achievement of the aim of this thesis can be verified in a concrete manner.

## 1.4 DELIMITATIONS

The research conducted in this thesis is mainly treated from a designer's perspective meaning that already developed fixturing solutions are excluded from efficiency analysis. Furthermore, the criteria search is delimited to the cost, time, quality and flexibility aspects of fixturing even though fields such as sustainability and ergonomics are important influencers in any manufacturing technology.

This thesis is delimited to flexible fixtures with focus on reconfigurable fixtures. Concepts such as modular fixtures and phase-changing materials are not studied in this thesis, although relevant research is presented in the theoretical framework. Due to the available projects, the experiments conducted are limited to assembly operations in the aerospace and automotive industries. Moreover, this thesis only focuses on the body design of flexible fixtures, meaning that related workpiece analysis does not form part of this research.

## 1.5 THESIS LAYOUT

The layout of this thesis starts with background information presenting outline problem formulations, aim and questions along with delimitations. . In Chapter II, the theoretical framework on fixtures and manufacturing paradigms are presented from a chronological perspective. In Chapter III, the research approach is outlined. In Chapters IV and V, results and discussion are presented. Finally, the conclusion will be drawn in Chapter VI.

# II

# FRAME OF REFERENCE

This chapter aims to provide fundamental knowledge about fixtures and manufacturing paradigms from chronological and technical perspectives. Furthermore, the terminology and arguments given in previous chapter will be elaborated upon. The chapter begins with a preface describing the framework of the collection of studies presented in this chapter. Later, the chronological evolution of fixtures, the fundamentals of fixture design process and manufacturing paradigms will be described. Finally, a theoretical synthesis is presented.

## 2.1 PREFACE: TRANSPARENCY

The references presented for fixtures are reduced from the collection based on the publications indexed in the databases Scopus® and Web of Science™. ™. The keywords utilized in all of the databases are *fixtur*, tooling*, *flexibl** and *reconfigur**. The delimitations for the results are on the subject area of *engineering*. For the Scopus® search, the keywords *fixture, flexible fixture, flexible tooling, tooling, fixturing, tools, jigs and fixtures* were also used. Furthermore, the publications where fixtures were eliminated such as so-called *fixtureless assembly* were excluded from the theoretical framework.

The chronological description of manufacturing systems given in section 2.5 is based on the available literature on manufacturing system paradigms collected from Scopus®. The initial search was done using the terms *manufacturing or production* and *system* or paradigm*, where the results were narrowed to *review* studies within the area of *engineering* and the subject area was excluded from natural sciences. The analysed studies were selected based on the number of citation and descriptive nature of the publication. Further delimitations were applied to the identified paradigms with respect to (i) fixture hardware evaluation, (ii) fixture hardware design and (iii) fixture utilization.

## 2.2 HISTORICAL EVOLUTION OF FIXTURES

With the increasing emphasis on Henry Ford’s mass production environment, a high-volume operation with the minimum number of changes in the product, work-holding devices were formulated around tailoring an efficient solution that satisfied the functional requirements of a specific workpiece. This particular definition constitutes the basis for fixtures and early solutions were formulated on the arrangement of four main components: A frame, body, a locator (or locating unit) and a clamp. The term *fixture frame* describes a mechanical unit designated for fixture foundation, usually in the form of a plate. The term *fixture body* defines the section of a fixture that establishes the connection from locators and clamps to a frame. Locators and clamps are the components that locate and secure the workpiece [3].

The fundamental idea of dedicated fixturing was the connection type between the fixture components. In the case of dedicated fixtures, these connections were realised by means of irreversible joints such as welding. When these components were secured to each other, the fixturing solution was tailored to a specific workpiece; hence the term *dedicated fixture* was coined [19]. The schematic classification of fixture elements in a dedicated fixture is illustrated in figure 2.

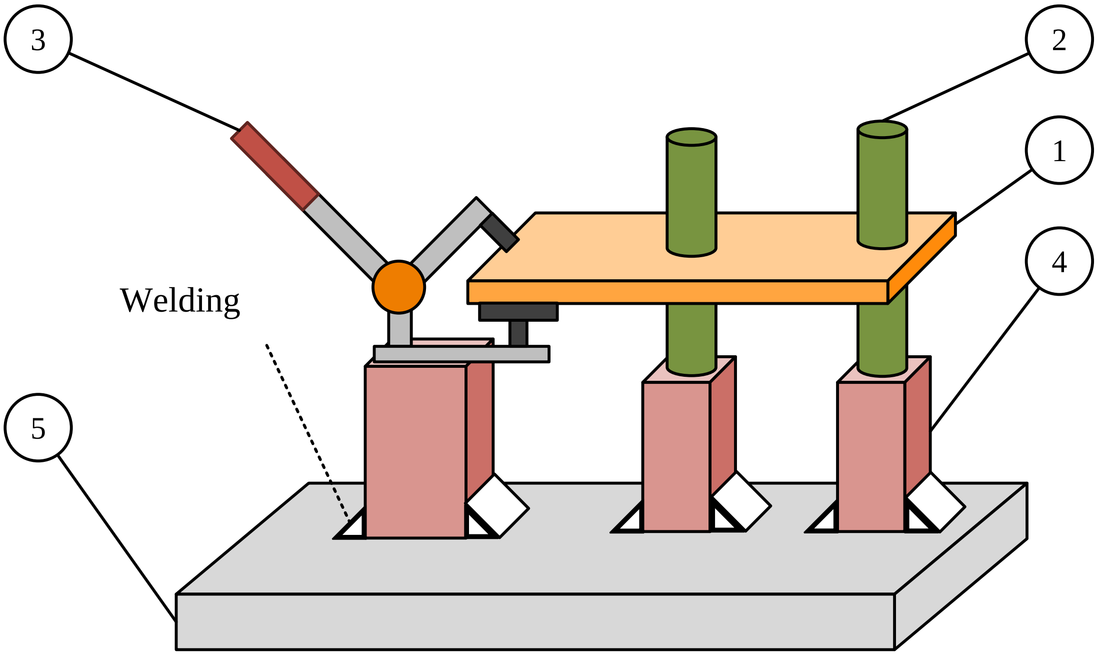



Figure 2. Typical fixture elements in a dedicated fixture: (1) workpiece, (2) locator or unit, (3) clamp, (4) fixture body, (5) frame

### 2.2.1 FROM DEDICATED TO FLEXIBLE: MODULAR FIXTURES

With the introduction of flexibility into manufacturing systems, the demand to adapt to a variety of products affected the shape and design of fixtures. Later, this demand for flexibility was met by the introduction of modular fixtures [20]. With modularity, two fundamental ideas – standardization and reusability – were introduced into fixture design [21]. Firstly, the parts that did not interact with the workpiece were standardized. Thus, the fixture frame and body in a dedicated fixture were replaced by multiple standard modular blocks and supplied as fixture kits. Secondly, the blocks were assembled to each other by means of reversible methods (such as the use of bolts) instead of welding [22]. Therefore, rebuilding the modular blocks and manufacturing only new locators and clamps for different workpieces was considered a solution for the challenge of flexibility [23]. The difference between modular and dedicated fixtures is illustrated in figure 3. Furthermore, these modular fixture kits were mainly categorized with respect to the type of elements and connection geometry. Shirinzadeh [24] and Dai, et al. [25] classified modular fixture types such as T-slot and hole-matrix plates systems. In these systems, the modular kits were made of standard components that allowed the designers to realise various geometries that were tailored to a specific workpiece and process. The final type of modular kit was proposed by Kihlman, et al. [13] in the form of plates connected to each other by beams.

The performance of modular fixtures in manufacturing systems was analysed based on flexibility, cost, time and quality perspectives. The outcome of these analyses indicated that a complete modular approach reduced the cost- and time-efficiency of high-volume production lines while increasing the complexity of their use and design [18, 26]. Therefore, industries such as aerospace and automotive manufacturing continued to use fixtures with both dedicated and modular features – which eventually created a gap for researchers to elaborate on the implementation of flexibility in fixtures such as in the form of reconfigurability [27, 28] and phase-changing materials [29]. An initial example of the use of phase-changing material was fluidised-bed systems to secure a workpiece [30]. Further research was conducted with magneto-rheological fluids by Rong, et al. [31] and de la O Rodríguez, et al. [32]. However, a recent review on phase-changing fixtures by Bakker, et al. [17] stated that the use of phase-changing materials is toxic; and therefore, considered less advantageous than other flexible fixture types.

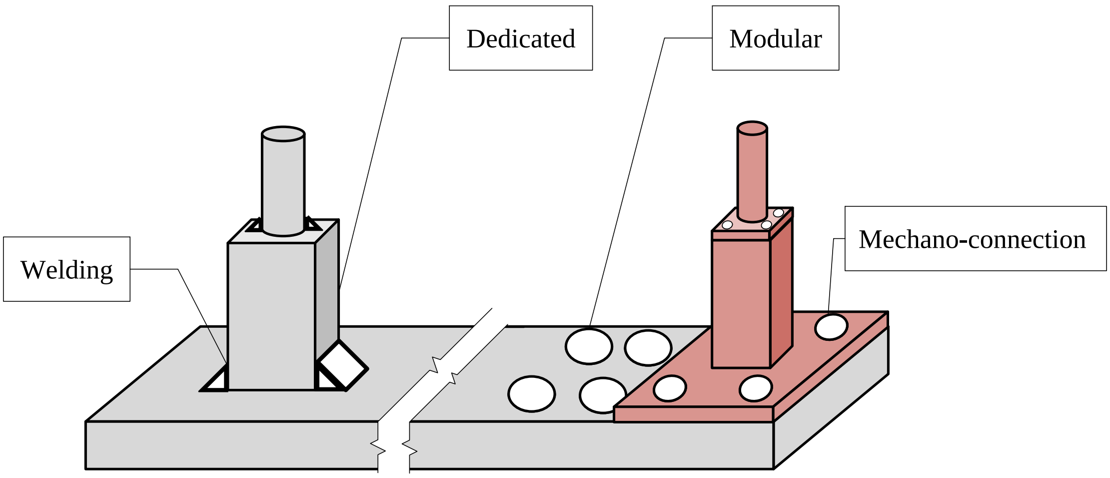



Figure 3. Dedicated and modular fixtures with welding and mechano-connection respectively.

### 2.2.2 RECONFIGURABLE FIXTURES

It is essential to understand reconfigurability and its meaning in the context of fixtures. Reconfigurability is defined as the activity of adjusting a fixture by utilizing built-in features such as the reconfiguration of a linear actuator’s leg length. An early example of reconfigurable fixtures was the use of robots to perform quick adjustments to fixture bodies and locators [33, 34]. The use of magnetic fixture frames and built-in clamps were among the initial concepts whereby a robot manipulator was utilised to reconfigure the fixture units [35]. Later, Chan et al. [36] presented reconfigurability in adjustable locators by using hydraulic and pneumatic actuation. Similar to internal locator adjustment, Shirinzadeh [37], [38] elaborated on the topic of different approaches to reconfiguration. Sela et al. [39] developed reconfigurable locators using sliding shafts to adjust the height of the locator. Another type of locator adjustment was presented by Du and Lin [40], with a workpiece being located with a so-called *three finger system* where actuation for locator reconfiguration was carried out using revolving pins attached to an electric motor and gear-coupling. Sherwood and Abbott [41] presented an actuator called “POGO™” where each locator was reconfigured with a pneumatic actuator, while Stone [42] and McKeown and Webb [43] also demonstrated the use of POGO™ in the aerospace industry. Magnetic features were also utilized in the locator reconfiguration where Walczyk and Longtin [44] created an array of pins reconfigured by a magnetic field. Al-Habaibeh, et al. [45] applied a similar fixture solution for components in aerospace manufacturing. A recent review on reconfigurable pin-based fixtures can be found in [46, 47].

With the introduction of Reconfigurable Manufacturing Systems, the application of reconfigurability was not only reliant on pin-based systems but also extended over kinematic structures [48]. An early example of a serially attached set of joints – also known as an *articulated kinematic structure or serial kinematics mechanism* – was presented by Yeung and Mills [49], [50]. In this solution, a fully automated gripper with 6 degrees-of-freedom (DOF) was proposed to replace a fixture. Arzanpour, et al. [51], [52] utilized an articulated robot with three suction cups arranged in a mechanism as a reconfigurable fixture for sheet metal assembly. Later came the use of Parallel Kinematic Machines (PKM). In this form of reconfigurable fixtures, researchers aimed to utilize different parallel kinematic structures in assembly processes. An early example of Stewart-Gough – also known as hexapod – platforms was demonstrated by Kihlman and Engström [53], [54]. In this setting, a robot manipulator was utilized to position the hexapods in an assembly cell with the securing of the final position carried out manually. Following the application of hexapods, different types of parallel kinematic structures were proposed with PKMs spanning from so-called "*tripods*" to "*octapods*" [13]. Later, the concept of PKMs was extended to include 3- and 4-DOF kinematic structures by Yu, et al. [55].

With the extensive work carried out on PKMs as reconfigurable fixtures, custom solutions were also emerging in response to the unique requirements of different processes and workpiece control. In this field – also known as active fixturing – reconfigurable fixtures with sensors were utilized to correspond to the variation throughout the process. Papastathis, et al. [56] presented a custom, reconfigurable fixture for aero-engine assembly and disassembly. De Leonardo, et al. [57] and Zhang, et al. [58] described reconfigurable fixture solutions for sheet metal manufacturing and assembly respectively. Furthermore, Rukshan, et al. [59] offered a reconfigurable fixture conforming to unconventional shapes. Olabanji, et al. [60] developed a reconfigurable fixture for press brakes. An example of a custom reconfigurable fixture with positioning clamps was developed by Papastathis, et al. [61]. Moreover, a reconfigurable fixture solution in serial kinematics form was developed by Keller [62] for Body-in-White (BiW) assemblies. Finally, an extensive review on active fixtures was recently published by Bakker, et al. [63].

### 2.2.3 SUMMARY AND CLASSIFICATION OF FLEXIBLE FIXTURES

As presented in earlier sections, various solutions exist for both modular and reconfigurable fixtures. However, over the history of fixture development, a number of systematic classifications have been published with respect to available fixture types and technologies. In this section, these review publications will be presented. Furthermore, a new classification structure will be described in order to assist the scope and delimitations given in section 1.4. Finally, this section will also draw a conclusion based on the chronology of fixtures.

The earliest classifications presented by Grippo, et al. [64] in 1988 and Shirinzadeh [24] in 1995 categorizes flexible fixtures by type; sensing, phase-changing, modularity and clamp – where physical adaptability was only acknowledged in modular/reconfigurable and phase-change fixtures. In 2001, Bi and Zhang [18] offered a physical form-based classification. In their review, classification was based on the number of components that comprised a flexible fixture. These categories were "*Flexible Fixture Systems with Modular Structure*" and

“*Flexible Fixture Systems with Single Structure*”. Under the modular structure category, the review presents reconfigurable fixtures. For single structures, the classification offers phase-changing and adapting clamp fixtures.

In 2001 and 2002 respectively, Kihlman [19] offered a relatively minor review in which fixture types were presented as *dedicated*, *modular*, *flexible* and *CNC-Controlled*. Furthermore, the study also introduces the concept of “*Affordable Reconfigurable Tooling*” (ART) as a new fixturing paradigm. Similar to early reviews, the final extensive review on fixture publications and patents was offered by Bakker, et al. [17] and classified flexible fixtures under seven categories. Besides the categories *modular*, *phase-change* and *sensor-based*, this study introduced *automatically reconfigured*, *pallet systems*, *pin-type* and *base-plates*.

Based on these classifications, two common points can be observed:

1. Flexible fixtures are categorized with respect to physical forms and features. In physical forms, fixtures are classified with respect to modular, pin-based, kinematics and phase-change. With respect to features, further categories are presented for actuation, sensor-use, position holding and connection-type, such as magnetics and fluid-beds.
2. As also demonstrated by the literature presented in section 2.1.2, a flexible fixture can include features from multiple categories.

Therefore, this thesis approaches fixture classification based largely on three categories. The first category, *rebuilding fixtures*, represents fixtures that require a rearrangement of the complete or partial structure to provide flexibility. The second category represents *phase-changing fixtures*. This category encapsulates all of the fixtures that utilize phase-changing technology to secure a workpiece. The third and final category, *reconfiguring fixtures*, describes fixtures that provide flexibility by internally adjusting certain parameters such as length change in PKMs.

Furthermore, these categories are complemented by features that can be classified as *actuation type*, *position or connection type* and *activeness*. The term *actuation type* describes the source of motion allowing flexibility. This category is further divided into internal automation, such as the use of motors, and external, such as the concept of utilizing an available robot, and manual actuation. The term *position or connection type* describes the underlying technology that connects and maintains all of the elements of a fixture. This can be divided into three subcategories: Mechanical, magnetic and fluid-based. The *activeness* of a fixture describes its ability to adapt and react to deviations in the process or workpiece by means of intelligence. Hence, this category is broken down into internally supported, such as the use of sensors and adaptive materials; externally supported, such as vision or measurement systems.

Consequently, the physical and feature-based classification can be presented in matrix form. Whether they belong to a single group or have common features, all of these fixturing solutions can be identified in this matrix. Furthermore, any emerging technology that operates beyond the range of physical form or features can be incorporated. The flexible fixture classification matrix is given in table 1 and the corresponding schematic is illustrated in figure 4.

Table 1. Flexible fixture classification matrix

| Feature \ Physical Form | | Rebuilding | Phase-changing | Reconfiguring |
|---|---|---|---|---|
| Actuation | Internal | | | |
| | External | | | |
| | Manual | | | |
| Position/ Connection Type | Mechanical | | | |
| | Magnetic | | | |
| | Fluid-based | | | |
| Activeness | Internally supported | | | |
| | Adaptive Material | | | |
| | Externally supported | | | |

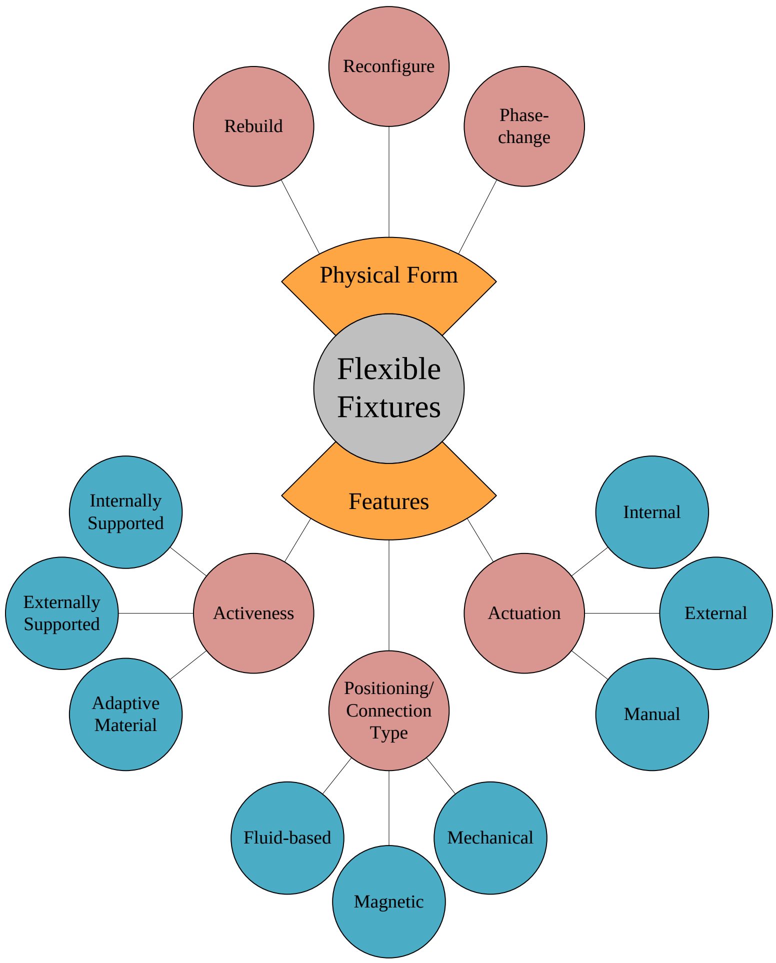



Figure 4. Flexible fixture classification based on physical form and features

## 2.3 FUNDAMENTALS OF FIXTURE DESIGN

A typical fixture design & development process is executed in five steps. Initially, the development process begins with the product (workpiece) and process analysis. The workpiece is analysed with respect to its material, geometry, dimensional features and restrictions. Later, the information regarding the manufacturing process, tolerance and operational restrictions is added. Then, these design criteria are elaborated with production and manufacturing system standards such as thresholds related to cost and safety [18, 65, 66]. The design process is illustrated in figure 5.

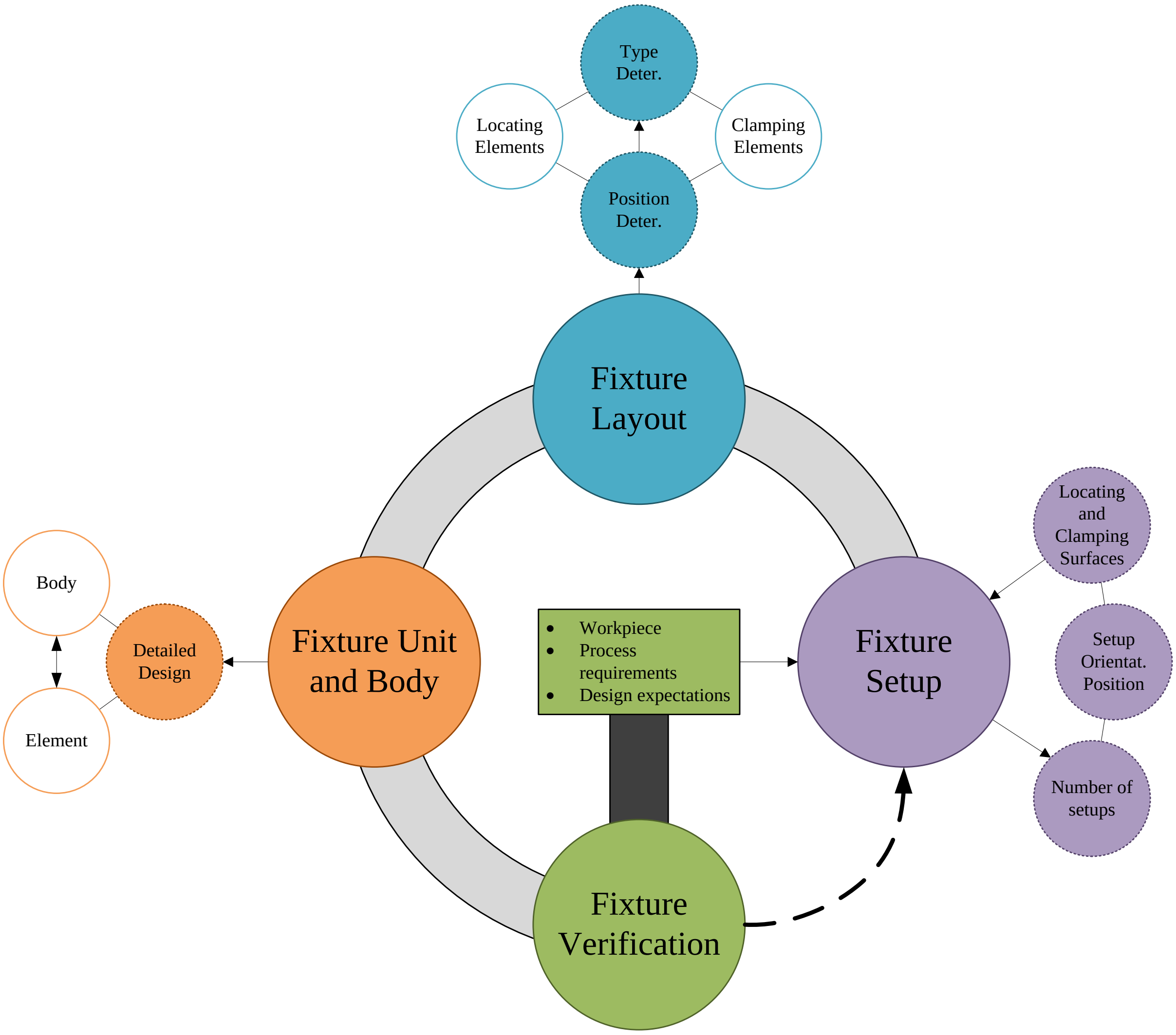



Figure 5. Fundamentals of fixture design process in five steps (I) Determination of specifications. (II) Fixture setup. (III) Layout planning. (IV) Unit and body design. (V) Verification. Adapted from Bi and Zhang [18], Rong and Bai [65] and Hargrove and Kusiak [66]

As the requirements are formulated, a fixture is then analysed for set-up planning. In this phase, the position and orientation of the workpiece with respect to a prospective fixture are determined. Specifically, the minimization of set-ups is ensured by analysing the features requiring operation. Subsequently, the locating and clamping surfaces for each set-up are determined [67]. In the layout determination phase, the locating datums and clamping points are generated based on the information provided in the set-up planning phase [68]. The information is processed with respect to methodologies for locating and clamping, a well-known example of locating methodology being 3-2-1 [69]. Another location method based on geometrical feature restrictions can also be used by coupling pins to controlled holes on the workpiece [70]. Unit and body design in phase four corresponds to the activities that enable the detailed design of locators, clamps and fixture body. In the final stage, the verification of the detailed design is realised based on the specifications given in the first stage, with the process being repeated for any deviations until the specified thresholds are achieved [71, 72].

In conclusion, fixture design is an interactive process through which the relationship between a manufacturing system and manufacturing technology can be observed. This dynamic relationship is based on the specifications generated as parameters from various elements of manufacturing systems such as product design and production systems.

## 2.4 COMPUTERISED DESIGN OF FIXTURES: A SEARCH FOR PERFORMANCE

With the introduction of Computer Integrated Manufacturing Systems (CIMS), the process of designing and developing fixtures became a focal point, with the automation of the process drastically reducing the design time. Researchers therefore began implementing algorithms to analyse, generate and evaluate the information flow for every stage in the fixture design process. The analysis phase – which also corresponds to the fixture set-up and layout planning phases – focuses on minimising the number of set-ups by finding the optimum workpiece position and orientation, so that the maximum number of features can be machined in a single set-up. Even though these algorithms fall outside the focus of this thesis, it is important to identify and give relevant examples to facilitate the reader's understanding. Therefore, the various algorithms utilized are rule- and case-based reasoning [73], kinematic [74, 75] and dynamical analyses [76] and artificial intelligence methods such as neural network [77, 78] and graph theory [79, 80].

The design of the fixture body is another integral part of the computerized fixturing process that has attracted the attention of researchers. In this stage, the algorithms for generating fixture units and bodies become the focus. Similar to layout planning, the main approach applied in this stage is to populate the locator and clamping points with modelling of dedicated and/or modular geometries, where proposed algorithms are categorised as *parametric modelling* [81], *case*- [82, 83] and *rule-based* [84, 85], *statics* and *dynamics analysis* methods [86, 87]. Finally, the verification phase takes place individually for each design step and final verification is done with respect to specific manufacturing and production system characteristics such as ease-of-use and cost and time limitations [88]. By completing the cycle of fixture design, the integration of computers became known as Computer-Aided Fixture Design (CAFD).

Besides the examples of different approaches given in this section, extensive reviews carried out into CAFD reveal the magnitude of researchers' efforts in [10, 18, 24, 37, 64, 66, 69, 72, 83, 88-92]. In these reviews, the applications of CAFD exhibit two commonalities. First, the unit and body design automation is heavily based on simple geometries that can be realised by fixtures of dedicated and modular design. Secondly, the dynamic relationship between manufacturing systems and their technologies is manifested in the form of parameter-based design – which in return has pushed the verification phase to focus on improved performance. In addition, the impact of CIMS showed a fundamental example of how paradigm shifts in manufacturing systems reshaped the design process itself, rather than just the fixture geometries. Consequently, the dynamics of performance – or in other words efficiency – is a correlation of system characteristics to fixture design and types.

## 2.5 THE DYNAMICS: INFLUENCE OF MANUFACTURING PARADIGMS

In earlier sections, this thesis demonstrated the shifts in fixture types and design in correlation to changes in manufacturing system philosophies. Two fundamental examples were the Flexible and Reconfigurable Manufacturing Systems. This section aims to identify and classify the influence of manufacturing systems from not only a fixturing but also a manufacturing-technologies perspective. A similar approach to previous chronological reasoning will be the framework for the interaction between manufacturing systems and fixtures.

Throughout the evolution of manufacturing system philosophies, there exist certain milestones that not only reshaped planning, control or operations in a manufacturing system but also the fundamentals of technological design. The earliest example of a shift of such magnitude was the introduction of Henry Ford's mass production [1]. The principle behind this production system was to utilize a certain type of product and manufacturing technology in a setting where minimum variety could be realised in terms of batches with the maximum possible number of products [93]. By enabling the mass production of standardized interchangeable components, a certain level of production quality could be maintained – which allowed the managerial elements to evaluate manufacturing performance based on cost-related metrics [94]. In the 1950s, a new concept emerged based on reducing set-up costs. This concept aimed to analyse batches of products and cluster fixtures with respect to the features that each workpiece required. This concept came to be known by the name Group Technology (GT) [95-97] . In 1980s, the impact of lean and world-class manufacturing introduced the quality and time-related metrics in order for companies to remain competitive in a market where relatively small customisation was playing an important role [98]. Within the framework of these new metrics, new technological understandings were emerging to increase the performance of manufacturing systems. One of these emerging concepts was the reduction of time and cost when changing batches with respect to a different product in terms of organizing operations. Thus, Single Minute Exchange of Dies (SMED) was proposed to reduce the set-up time by analysing the activities and planning the production to enable an uninterrupted flow of products [99].

As these paradigms were achieving a level of maturity, another milestone in manufacturing systems was reached. This maturity, along with the increased competition, required more customisation than had previously been the case [100]. Thus, this emerging need for greater flexibility in manufacturing systems manifested in a physical form – which led to coining of the term Flexible Manufacturing Systems (FMS) [101]. As the expected performance of the elements of manufacturing systems was being reshaped; the parameters to measure them followed the same process. Hence, *flexibility* was added to *cost*, *quality* and *time* [102, 103]. As described in earlier sections, the introduction of flexibility as a performance parameter created new metrics such as machine flexibility; and this process of continuous evaluation eventually resulted in the emergence of new fixturing technologies such as modular fixtures [104].

As these developing technologies were being deployed in manufacturing industries, performance metrics failed to show the promised results from FMS. Therefore, optimisation in the application of flexibility became a driver for both academia and industry [26]. Through these efforts, a new manufacturing philosophy evolved with a characteristic named as agility. Introducing the optimisation of flexibility over the network of manufacturing activities, this resulted in Agile Manufacturing Systems (AMS) to address the performance challenges [105-107]. On the other hand, AMS understanding did not aim to reshape the technology; therefore, a new manufacturing philosophy emerged focusing on production control and planning, reconfigurability in AMS, as addressed by Kusiak and Lee [108] and Lee [109] in 1997.

Concurrently, Rogers and Bottaci [110] offered a very similar approach to reconfigurability with a study offering a new manufacturing paradigm called Modular Production Systems (MPS). Later, the concept of reconfigurability was expanded to the manufacturing system level with a complete description of technological characteristics by Koren, et al. [48]. This concept was termed Reconfigurable Manufacturing System (RMS) as introduced in section 1.1. In RMS, the characteristics offered by Mehrabi, et al. [111] in 2000 and Koren [112] in 2013 were

- *customised flexibility* meaning that each technology provides only the required amount of flexibility,
- *convertibility* meaning that a production system is capable of switching between products of the same family,
- *diagnosability* as in the quick ramp-up of a production system,
- *modularity* as in the capability of replacing manufacturing technology rapidly,
- *integrability* as in the capability of manufacturing technologies to interact with each other,
- *scalability* as in the capability of a production system to add/remove technologies with respect to volume.

Throughout the evolution of manufacturing systems, new paradigms aimed to bring in a novel understanding on the execution of production systems and characteristics of manufacturing technologies. However, the impact reached further than the physical boundaries, affecting the measurement of performance. From mass production to RMS, Performance Measurement Systems (PMS), aiming to evaluate the impact of different manufacturing approaches, evolved from purely cost-related metrics to a set of metrics grouped under cost, quality, time and flexibility [113-115]. Folan and Browne [116] and Waggoner, et al. [117] argue that the reasoning behind the evolution of PMS is that sets of metrics can only be grouped on a general level whereas individual metrics need to be adapted with regard to the various elements of a manufacturing system. On the other hand, individualised PMS metrics also offer a benchmark for academia and managers to create the shifts that facilitate the evolution of manufacturing systems [118].

In this section, the milestones that affected manufacturing technologies were presented in order to exemplify the dynamics between manufacturing philosophies and technologies. As a revolutionary idea, mass production introduced standardised, large-scale production and corresponding robust technologies. Aiming to reduce the capital costs of fixtures, GT utilized the information on products in a family to reshape the fixture design process. With increased competitivity, the concepts of lean manufacturing and SMED emphasised the importance of providing technologies and services that can meet the challenge of reducing cost and set-up time. Finally, the emergence of flexibility initiated the concept of FMS and the efforts to control and optimise the flexibility of manufacturing technologies through AMS and RMS paradigms and their proposed characteristics. Consequently, the dynamics between philosophy and the technology were captured by means of characteristics and metrics. The chronological representation of these dynamics is presented in figure 6.

## 2.6 THEORETICAL CONCLUSION: UNDERSTANDING THE GREY

This chapter of the thesis provided the available information about the chronology and design of flexible fixtures. From a chronological perspective, flexible fixtures were manifested in physical form requiring rebuilding, phase-changing or reconfiguration where each solution was diversified with numerous actuation, activeness and connection types. Hence, the versatility of the available flexible fixture solutions indicates that an aspect of fixturing performance is the reliance on the capabilities of the available technology. Furthermore, the research conducted on fixture design points to the conclusion that designing with respect to given parameters is an enabler in the application of flexible fixturing as with the fixtures of rebuilding nature. Thirdly, shifts in the understanding of manufacturing systems affected the characteristics of fixtures and the chances of applicability by means of affecting performance metrics. Subsequently, these factors can be formulated as (i) technical versatility and the capability of available technologies (ii) a well-established, methodical design process (iii) development with regard to given characteristics and performance criteria.

In the success of modular fixtures, the aforementioned factors contributed to and enabled fixtures of rebuilding nature to be optimised to given performance requirements. However, the dynamics between these factors remain unknown for other flexible fixture solutions. Even though technological versatility is observed to exist, the aspects of capability, design and performance are yet to be analysed. Consequently, the lack of analysis leads to an *uncharted territory*, where improved efficiency through the identification and implementation of performance parameters in reconfigurable fixture can light the way.

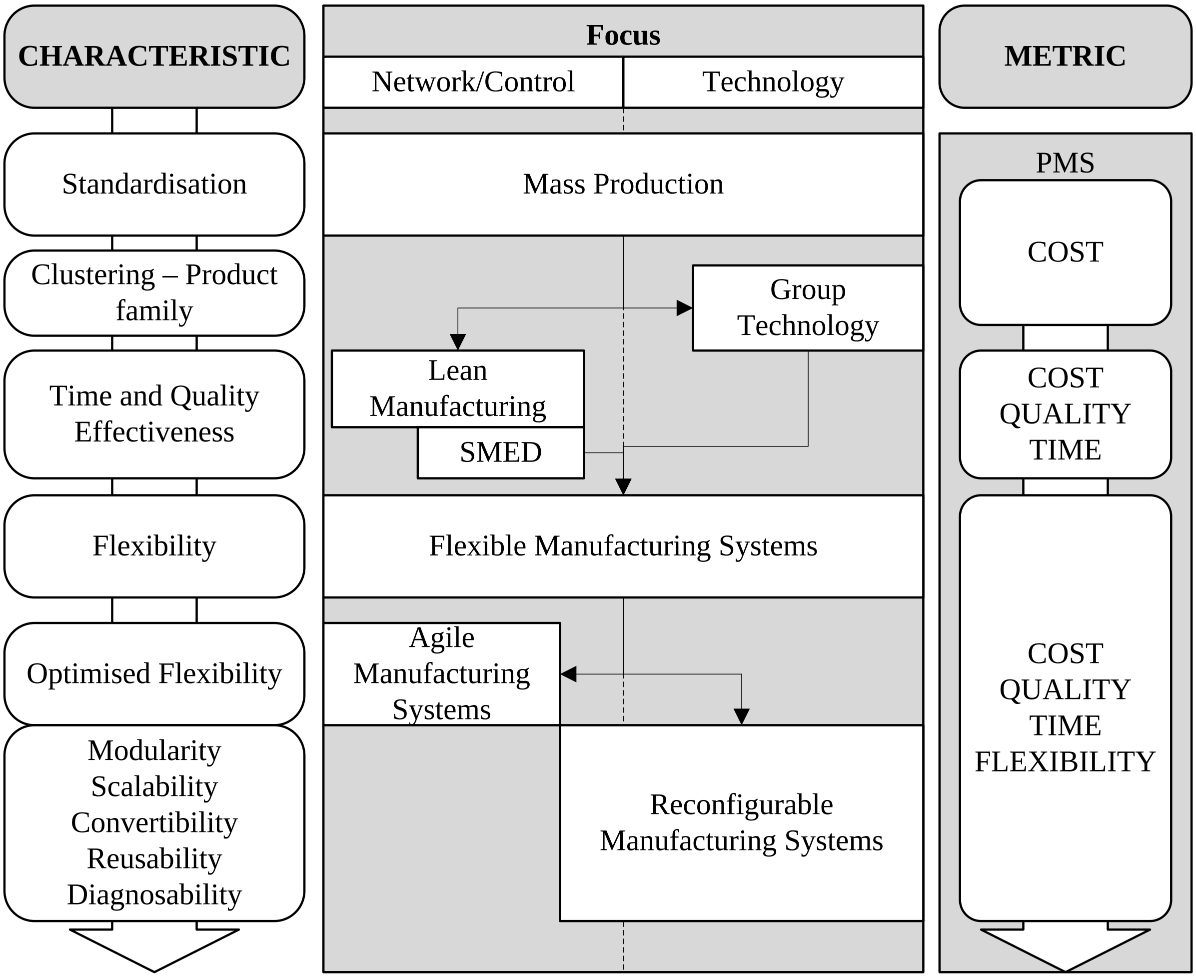



Figure 6. Chronology of the shifts in manufacturing systems, characteristics and metrics

# III

# RESEARCH APPROACH

The progress of science relies on the methodical development of knowledge. This chapter focuses on the deployment of the scientific method in order to fulfil the aim of this thesis. The first section describes the nature of the fixture research with respect to the thesis' aim and research questions. Later, available research methodologies and methods are presented.

## 3.1 PREFACE: RESEARCH APPROACH AND TERMINOLOGY

Kothari [119] and Maxwell [120] signify that the systematic process of research (also known as research design) plays an important role in defining what constitutes good research. In this process, Crotty [121] offers a hierarchy of definitions in order to identify the elements of systematic research. In his classification, *Research Methodology* is defined as the process by which each stage of research, along with any relevant information, is well described. Furthermore, the types of activity are grouped under the content of methods where a method is the practice of gathering data in a repeatable manner.

Bryman and Bell [122] describe the correlation of research to theory on the basis of *guide* vs. *outcome*. In the case of *guide*, the theory leads the researcher to deduce a hypothesis where the hypothesis is analysed by empirical means. In the *outcome* approach, the observations and findings are generalised to form a theory that is the outcome of the research. The first approach is generally known as the *deductive* approach (reasoning or sometimes referred as logic). The latter, on the other hand, is referred to as *inductive*. Creswell [123] offers a similar definition on the relationship of theory to research but with certain differences in the use of terminology. The use of theory as the guide approach, in this case, is referred to as quantitative research based on the deduction that this form of reasoning often utilizes numerical data collection methods. Qualitative research, then, refers to the generalisation of findings as with inductive reasoning. However, Bryman and Bell [122] emphasise that both approaches may utilize data collection methods of both quantitative and qualitative natures; therefore, the relationship between theory and research as inductive and deductive offers an easier understanding. Consequently, this thesis conforms to the classification of deductive and inductive research approaches, and treats quantitative-qualitative as data collection methods.

## 3.2 AIM, QUESTIONS AND THE NATURE OF THIS RESEARCH

The aim of this thesis is to increase the efficiency of flexible fixtures in manufacturing industry. Thus, the phrase *increase the efficiency* plays a key role in establishing a research approach for this thesis. In the exploration of the dynamics of fixture efficiency, the theory presented in a chronological manner in Chapter II revealed three distinct efficiency perspectives. The first was the creation of various technological solutions to technical problems and physical manufacturing-system needs. The second perspective was the response to the need for methodical development as observed with modular fixtures in terms of a well-established design processes, such as CAFD. The third and final perspective was the development of flexible fixtures based on the characteristics and performance of manufacturing systems.

When the research questions are correlated with the three fixture efficiency perspectives, the following relationship can also be established. For *RQ1*, the answer will fall within the scope of perspectives one and three where *technical capabilities*, *characteristics and performance* will provide the criteria for flexible fixture efficiency. Therefore, the answer to *RQ1* needs to provide:

- The criteria related to technical and performance capabilities of versatile fixture technologies
- The metrics to measure the efficiency criteria for flexible fixtures

*RQ2* is related to the second perspective, where the establishment of a methodical design process consequently constitutes the partial answer. The remaining part of *RQ2* focuses on the utilization of the methodical process to increase the efficiency of flexible fixtures. Therefore, the verification and validity aspects of *RQ1* and methodical development process can also be used to answer the second part of *RQ2*. Hence, the following should be provided by the answer to *RQ2*:

- A methodical development process
- Verification and validation of the increased efficiency of fixtures

The distribution of research questions over the aim and the perspectives is illustrated in figure 7. If the three perspectives were reanalysed based on the content requirements, then it is possible to identify the need for a framework that enables researchers to evaluate, reapply and iterate based on the results of conducted research. This particular situation is essential in the evaluation of technological capabilities and verification of efficiency criteria.

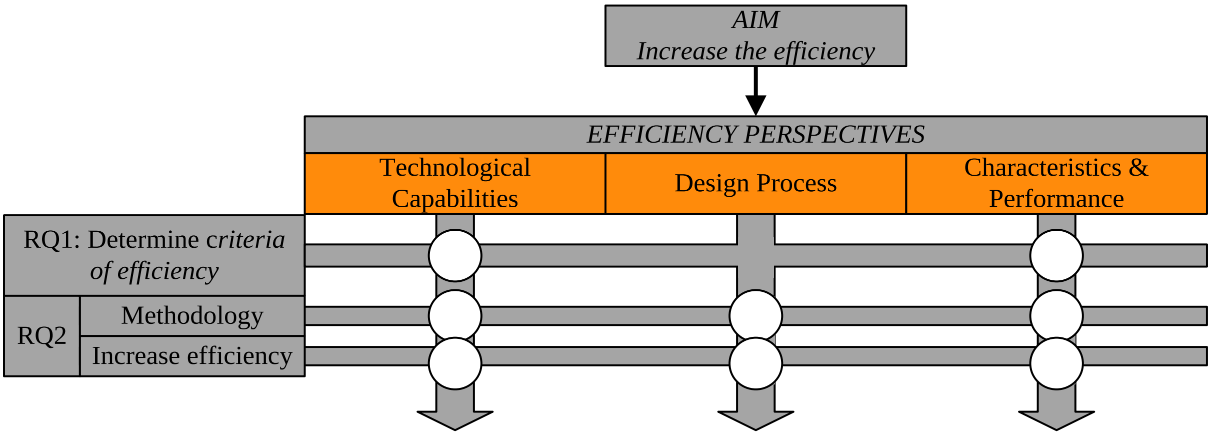



Figure 7. The correlation of research questions to the fixture efficiency perspectives.

## 3.3 RESEARCH FRAMEWORKS

The essential nature of the research questions requires a systematic inclusion dictated by a design process and evaluation of certain capabilities and performance. Therefore, the concepts of design and development play a key role in providing a framework that can categorise and offer a path of stages to achieve the aim of this thesis. Based on that reasoning, the following subsection will introduce the available frameworks in different research disciplines and evaluate their fitness for use of this thesis.

### 3.3.1 AVAILABLE FRAMEWORKS

In computer science research, it is important to establish a bridge from research to deployment; thus, a framework that correlates the different research approaches to applications in the field is essential [122]. For this purpose, researchers in the field use frameworks that focus on the development aspect of various software systems. An example of such a framework, *Systems Development,* is offered by Nunamaker Jr, et al. [124] as shown in figure 8. In this framework, the researcher is encouraged to start with *theory building*. This term is associated with identifying the relevant theories in the body of knowledge that can help researchers to convert the nature of a problem or phenomenon into a deterministic and repeatable system. In the second stage, researchers are advised to formulate *experimentation* to test the theory in order to evaluate whether it fits the phenomenon. In the third stage, *observations* in the form of case studies and surveys are proposed to gain more insight into the conditions that may inhibit possible outcomes. In the final stage, the system is developed using the information obtained in the earlier stages to draw specific conclusions that contribute to the body of knowledge.

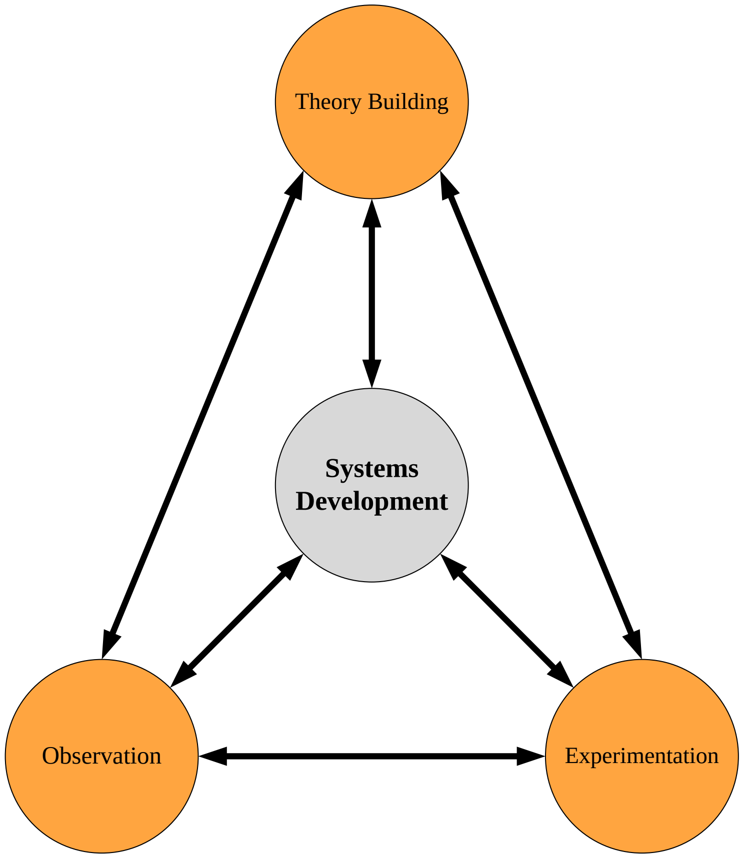



Figure 8. Systems development framework (adapted from Nunamaker Jr, et al. [124])

There is another approach that provides a framework for industry-related research by emphasising the importance of collaborative environment between industry and research. Developed by Potts [125], *industry-as-laboratory* offers iteration-based research in close collaboration with industry. Within this framework, a study is carried out in steps of solution versions where each version is then applied to the industry for experimental purposes. This incrementally developing and experimentally developing research framework allows the evolution of research rather than an experiment fully realised in a single step. The *Wingquist Research and Implementation Model* [126] was developed with a similar purpose in mind and focuses on the fusion of research challenges and industrial opportunities into research goals. Later, the research challenge is manifested in product form via demonstrators in forms of prototyping, processes and evaluation.

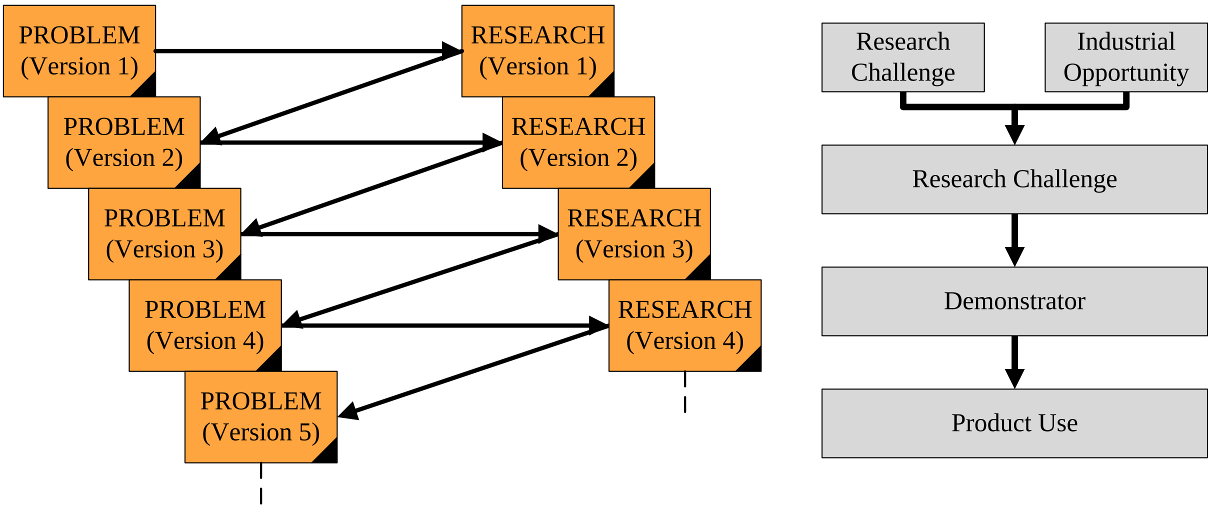



Figure 9. (a) Industry-as-laboratory approach adapted from Potts [125] (b) Wingquist Research and Implementation Model redrawn from [126].

Another branch, rather from a general perspective, is the concept of applied research. In this concept, Eckert, et al. [127] proposes the *Eightfold Path model of design research* (also known as *Spiral of Applied Research*, see figure 10) where the model is executed in four main steps with evaluation stages distributed in between. First, the researcher is encouraged to understand the behaviour behind a development and design process by means of empirical studies. These studies are within the scope of both quantitative and qualitative data collection methods. By validating the empirical studies, the second stage is executed in order to develop a theory of how this phenomenon can be understood. This theoretical learning is then evaluated so that the tools and procedures that will convert the theoretical learning into application can be developed in the third stage. After these tools are evaluated by means of demonstrators and prototype tests, the introduction of the tools into industrial use is realised in the last stage.

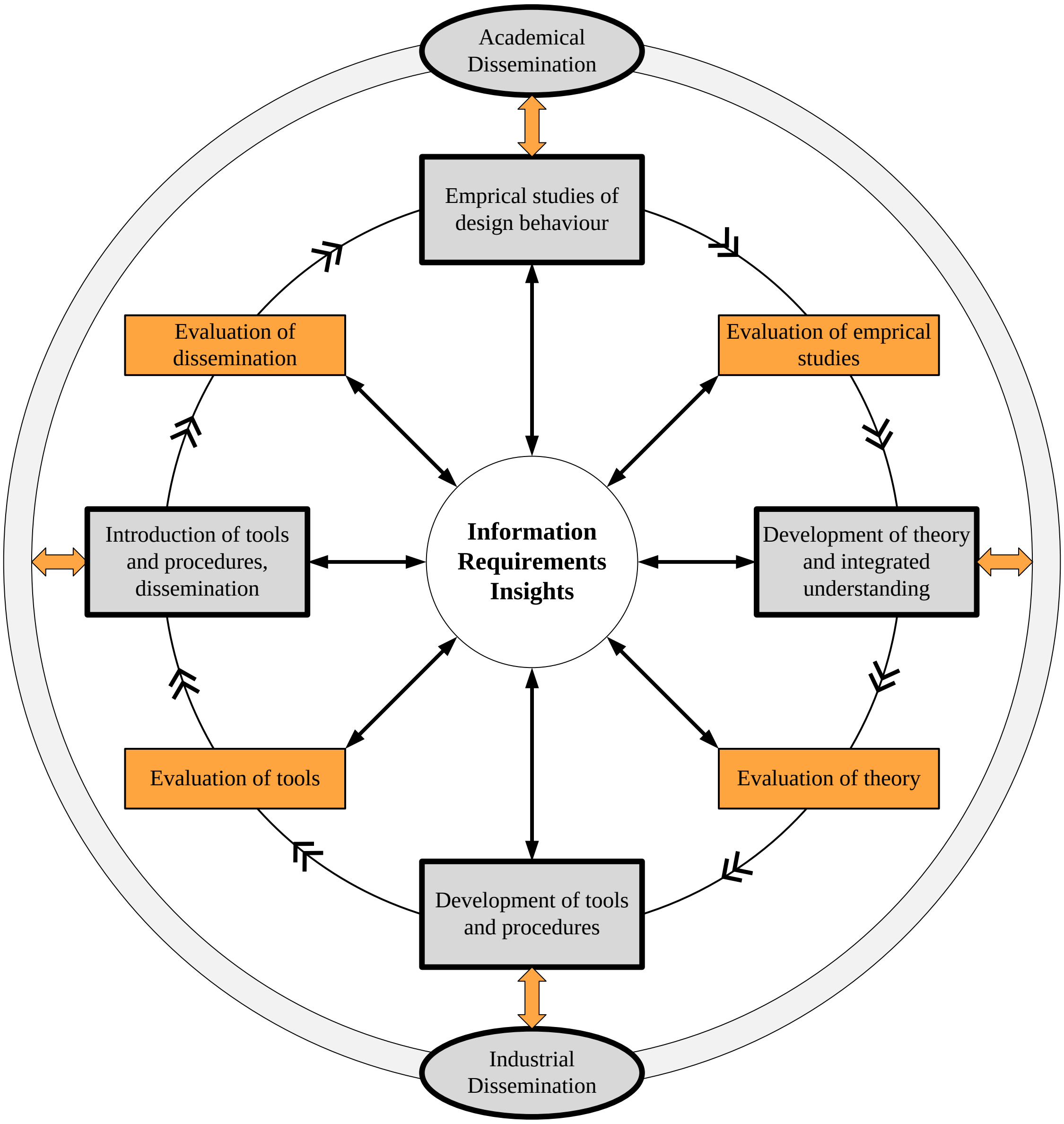



Figure 10. The spiral of applied research (redrawn from Eckert, et al. [127])

Design Research Methodology (DRM), developed by Blessing, et al. [128] and shown in figure 11, is a framework of phases created to support design and development research. In this framework, research is analysed in four distinct successive steps. In the first stage, *Research Classification*, researchers are encouraged to identify the established body of knowledge and develop goals, criteria, hypothesis and questions by means of literature reviews. In the second stage, known as *Descriptive Study I*, research is carried out in order to develop an understanding of the identified phenomena. In the body of descriptive studies, a reference model complemented with success criteria is developed by means of qualitative and quantitative studies ranging from interviews to experiments. Once the reference model is established, DRM proceeds to the *Prescriptive Study* stage. In this type of study, the aim is to develop an impact model based on the outcome of the earlier stages to improve the design and development process. The last stage, known as *Descriptive Study II*, focuses on the evaluation of the impact model based on the success criteria by means of empirical methods.

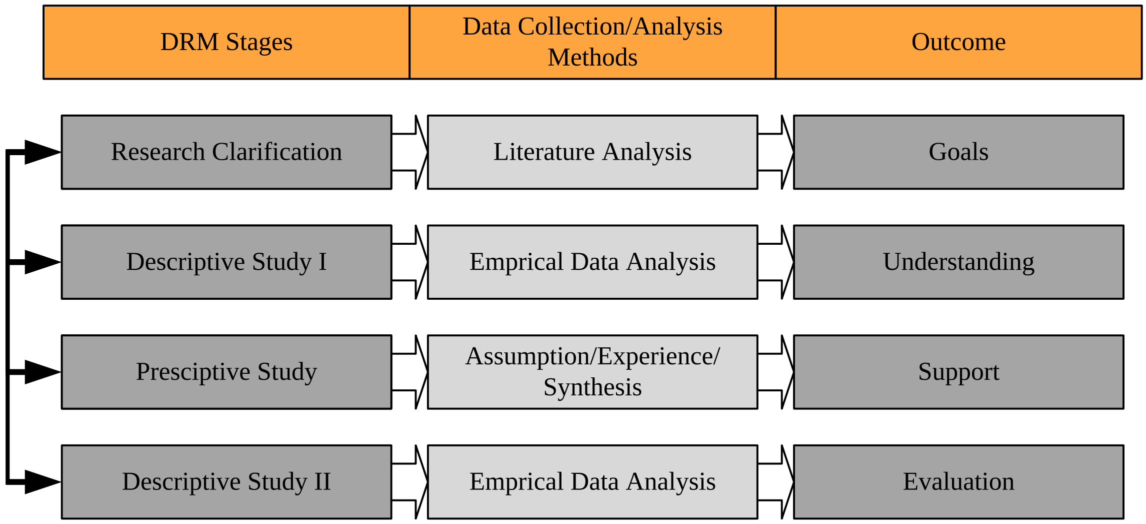



Figure 11. DRM – Design Research Methodology. Stages, Methods and Outcome. (Redrawn and adapted from Blessing, et al. [128].)

### 3.3.2 APPLIED FRAMEWORK

The nature of the research questions and its correlation to the phenomenon presented in section 3.2 is a fundamentally influencing factor in the selection of a framework for this thesis. An initial understanding of the nature of this research clearly shows a need for inductive reasoning that leads to a broader theory based on the knowledge that fixture efficiency does not rely solely on technological capabilities but also requires an exploration of the remaining perspectives. Therefore, the exploration phase is correlated to the applied aspect of this research. When the aforementioned frameworks are analysed, a commonality can be observed whereby each framework offers an iterative way to build knowledge. However, the frameworks industry-as-laboratory and systems development mostly focus on the cyclic repetition of the plan-develop-test phases. This repeating pattern is essential in terms of a research framework where the research questions are general in nature and do not imply a certain path or expected result.  Furthermore, the spiral of applied research is also based on repeating phases where the framework offers open-ended learning and does not aim to measure the success criteria. However, in correlation to the research questions and the specific aim of this research, an argument can be made regarding the requirement for a stricter framework where the intended research is carried out in successive steps that aim to fulfil certain criteria.

Contrary to the aforementioned frameworks, DRM's non-cyclic and goal-oriented approach aligns to the nature of this research in a more robust manner. Considering the argument in section 3.2 on the three perspectives and their correlation to the research questions, certain expectations are imposed on this research. As DRM establishes an outcome for each stage by complementing with success criteria, the imposed expectations can be facilitated in the DRM framework. For example, in the stage *Descriptive Study I* an understanding of the phenomena is expected. Due to the exploratory aspect of the three perspectives, such stage plays an important role in developing a reference model and evaluating the understanding. This establishes a reliable frame to describe fixturing efficiency and offer a reference model. Since the remaining stages focus on the development of impact model and measuring the actual impact, these stages coincide robustly with the specific aim of this research where the developed impact model and its verification inherently answers *RQ 2*.

Consequently, the DRM framework has been chosen as the guiding method for this research and the following section will introduce the data collection methods deployed.

## 3.4 DATA COLLECTION METHODS

DRM divides sets of data collection methods with respect to each stage where the research efforts are proposed to start with a literature-based review. Later, the methodology proposes to engage with empirical data analyses by means of both quantitative and qualitative methods. Among the acknowledged quantitative methods, there are surveys, experiments and questionnaires. From a qualitative perspective, DRM utilises observational methods, interviews and case studies. In the life span of DRM, seven combinations of research studies are disseminated over the four stages. The types of studies are classified as *review-based*, *comprehensive* and *initial*. The review-based studies employ literature reviews and focus on evaluating the available theory. Comprehensive studies are comprised of literature reviews and empirical studies conducted by the researcher. Initial studies represent the ending of a research lifespan and are intended to evaluate and reuse the generated knowledge. The possible combinations of research studies are illustrated in table 2.

Table 2. Type of studies for DRM as remade from Blessing, et al. [128]

| | *Research Clarification* | *Descriptive Study I* | *Prescriptive Study* | *Descriptive Study II* |
|---|---|---|---|---|
| **1** | Review-based | Comprehensive | | |
| **2** | Review-based | Comprehensive | Initial | |
| **3** | Review-based | Review-based | Comprehensive | Initial |
| **4** | Review-based | Review-based | Review, Initial, Comprehensive | Comprehensive |
| **5** | Review-based | Comprehensive | Comprehensive | Initial |
| **6** | Review-based | Review-based | Comprehensive | Comprehensive |
| **7** | Review-based | Comprehensive | Comprehensive | Comprehensive |

This thesis is a Type 7 study as defined above. The research conducted utilises two data collection methods, namely literature studies and empirical studies. The initial literature review was presented in Chapter II of this thesis for the *Research Clarification* phase. Furthermore, the Publications A and B elaborate on the research clarification by means of literature reviews. In the *Descriptive Study I* phase, this thesis presents three publications. In Publications A, B and C, the data collection methods follow a literature review and an empirical study in the form of experiments conducted to develop an understanding. Publication D remains to be in conjunction with theoretical and experimental data collection where the analysis and synthesis of available theories from various disciplines is experimentally tested. The experimental studies for all publications were preferred for the phenomena in all publications were possible to isolate from the occurring environment. All publications included in this thesis, therefore, are considered comprehensive.

### 3.4.1 DATA COLLECTION: PROJECTS & PUBLICATIONS

In this thesis, projects were the main means of the data collection. Automated Process Control BiW (AProC) and Machine Optimization Learning (MachOpt) are the automotive industry related projects both of which utilize a spot welding process and reconfiguration of fixture parameters with different automation levels. The content of the projects is to enable the inline configuration of process parameters by adapting the assembly fixtures to an input given by artificial intelligence using case-based reasoning. Initially, the inline measurement is conducted on the geometrical features of a sample workpiece in order to determine the deviation from nominal values. By evaluating the deviations, the artificial intelligence system proposes a solution based on similar cases. In AProC, the automation of flexible fixture reconfiguration is of a manual nature whereas MachOpt aims for a fully automated reconfiguration scheme. Publications A and D utilize the findings from AProC and MachOpt respectively.

Low Cost Manufacturing and Assembly of Composite and Hybrid Structures (LOCOMACHS) is a European Union funded project within the aerospace industry. The aim of the project is to enable the new build philosophy for a wing assembly process that aims to minimise the wastes and manual labour involved. Specifically, the sources of waste are identified as shimming (to level two or more relative points, surfaces or planes by means of adding extra components in between), variation and temporary assembly operations. The solutions presented in Publications B and C adapt to the geometrical variations and reduce the need for shimming operations by means of fully automated reconfigurable fixtures capable of intelligent wing box assembly.

## 3.5 VERIFICATION & VALIDITY

The concepts of *verification* and *validity* often have different meanings in various disciplines. In social sciences, *validity* is a term coined to describe the correctness of the findings and conclusions [120]. Different requirements on validity have been proposed by Cook and Campbell [129]. Based on four types of validity – *statistical conclusion*, *internal, construct* and *external*, a validity assessment can be made for scientific purposes. For s*tatistical conclusion validity*, the important aspect is to identify the relationship between different variables in the study. The *internal validity* aims to reveal the facts about these variables with regard to if they affect each other (also known as *causality*). The *construct validity* aims to shed light on the generalisability of the individual results into more abstract constructs. *External validity* is the generalisation of the valid construct into broader setting and time span. For research employing qualitative studies, Creswell and Miller [130] offer validity evaluated from *trustworthiness*, *authenticity* and *credibility* perspectives; where strategies such as triangulation and member checking are means of validity analysis. However, the "measurement" of validity is done by identifying the threats and offering countermeasures in terms of narrowing the findings with respect to *generalisability* [128]. Finally, the concept of reliability is a key-factor describing how repeatable the data collection is regardless of the research type [131].

On the other hand, the verification is to evaluate that the each element of the research process generates meaningful results. Considering the many influencing factors involved in design research, Buur [132] approaches the concept of verification in engineering design from two perspectives. V*erification by acceptance* (also known as *external verification*) focuses on the acknowledgment of the experts in the field. *Logical verification* aims to verify the internal dynamics of the conducted study, where the *consistency, coherence, completeness* and *ability to explain unique phenomenon* of obtained findings are the key elements.

When an analogy is made to the aim of this thesis, the application of the verification and validation concepts are as follows. The process of verification was ensured by means of Publications A, B and C, which have undergone peer review and been presented in conferences to a broader audience for acceptance. Furthermore, each publication's results (demonstrators) were shared and acknowledged by the project members. Publication D has been submitted to a journal in which results have been empirically tested. A further analysis of verification and validation is offered in section 5.2.

## 3.6 PUBLICATIONS AND RESEARCH METHODOLOGY

The distribution of publications with respect to DRM is illustrated in figure 12. Publications A and B mainly contribute to *Research Clarification* by means of empirical studies and offer experiments on existing technologies. Since experimental studies also contribute to the understanding of the existing phenomena, these publications are considered partially within the descriptive study I. Publication C is a collaboration between the university, industry and research institutes. Thus, it involves experiments and data collection from multiple cases within the LOCOMACHS project. In this publication, the utilization of the main reference model for development is presented and experimentally verified through demonstrators and acceptance of the collaborating partners. Moreover, the reference model presented in this publication is based on the knowledge gained from Publications A and B. In the last step of the flow, Publication D focuses on elaborating the understanding of the earlier reference model in Publication C and offers experimental verification by utilizing a case from automotive industry.

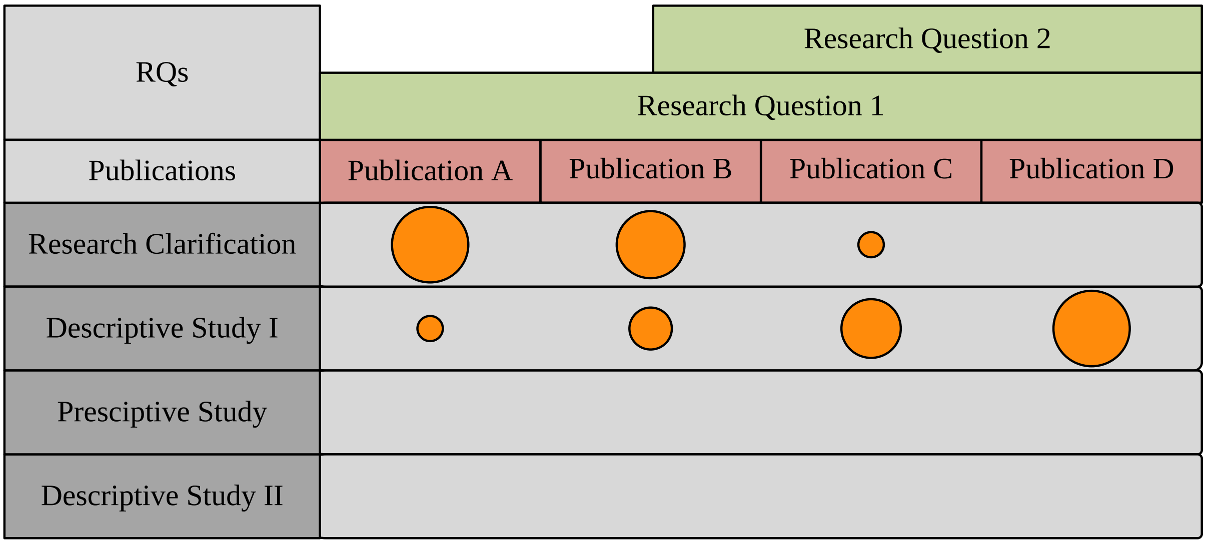



Figure 12. DRM and the publications of this thesis (each publication’s focus and its magnitude are represented by an orange circle and the diameter respectively).

# IV

# RESULTS

This chapter provides the knowledge flow of this thesis along with its key findings. Initially, the knowledge flow map is presented in order to facilitate the understanding and coherence of the chapter. Later, each publication is presented in a separate section. The main structure of each section is as follows: *Description*, *Goal*/*Aim*, *Methodology/Procedure*, *Experiments* and *Results*.

## 4.1 PREFACE: KNOWLEDGE FLOW

In the research clarification phase, publication A focuses on the application of available fixturing solutions into automotive industry. By utilising the theoretical knowledge, Publication A remains in the domain of reconfigurable fixtures with manual actuation. In contrast to Publication A, Publication B studies an automated reconfigurable fixture with externally supported active features in the aerospace industry. Both of these publications aim to clarify the phenomenon and elaborate on the existing knowledge on reconfigurable fixtures within different domains. Furthermore, the knowledge gained by the results of Publication A is also utilised as input for Publication B. Moreover, Publications A and B contribute to answering *RQ 1* in terms of determining the criteria related to technological capabilities. Publication B, as an addition to initial research question, builds a foundation for *RQ 2* by identifying the different aspects of flexible fixtures. From a research methodology perspective, the main objective of these publications can be considered mainly as research clarification and the development of an understanding.

The results and knowledge gained in earlier publications create a foundation for Publication C in which the study in Publication B is extended to a larger scale by collaborating with the partners and utilising greater experimental data. In this publication, a product-development approach is used to demonstrate how the methodical development of fixtures can capture the requirements of different processes accurately and repeatedly. This publication in particular offers experimental data for the verification of *Research Clarification* phase and the outcome of earlier publications. Publication C, therefore, contributes to the understanding in *Descriptive Study I* phase and focuses on providing answers to both research questions.

Publication D contributes only to the understanding and represents the final step in this thesis. Hence, it encapsulates the results of previous publications based on the methodical development approach offered by Publication C. This publication aims to answer both research questions from a theoretical perspective where an experimentally verified comparative method with metrics is proposed. The results contained in the publications will be presented in subsequent sections and summary of the knowledge flow can be seen in figure 13.

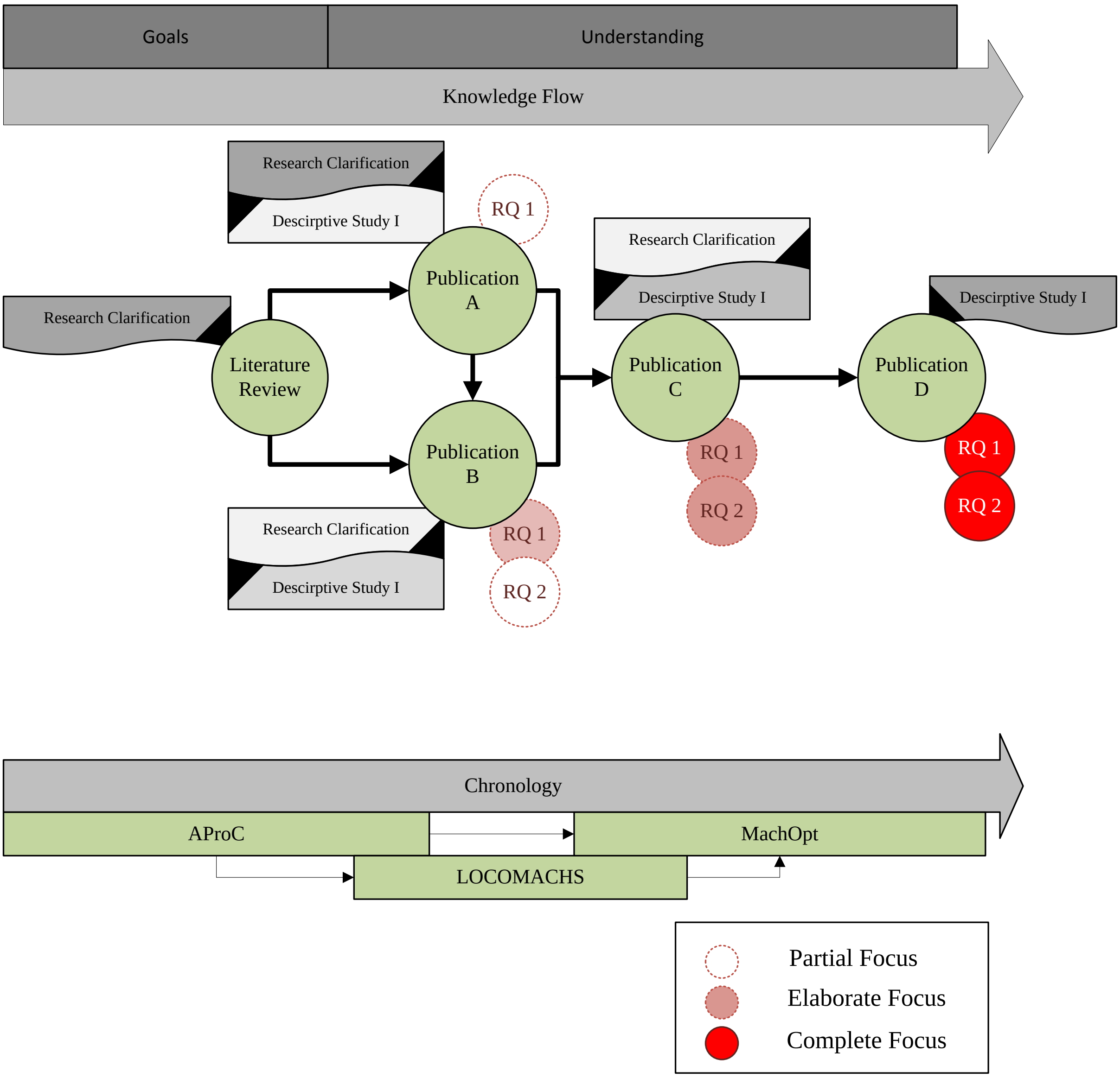



Figure 13. Knowledge flow and chronology of publications with respect to DRM and research projects

## 4.2 PUBLICATION A

***Development of Affordable Reconfigurable Tooling in Car Manufacturing Cells - A Case Study***

*Description*

The study in this publication was carried out with respect to the correction of workpieces through the utilisation of flexible fixtures in BiW assemblies. The content of the project aimed to enable the implementation of Case-Based Reasoning for an inline production system that could interact with a measurement system and fixture configurations.

*Aim*

The aim of the study is to explore and implement existing flexible fixturing solutions into the automotive industry in order to facilitate the corrective actions and flexibility required for product changeovers.

*Research Approach and Utilised Fixture Theory*

Initially, the publication presents the existing theory and section of relevant literature for flexible fixtures. Second, the utilised fixture design theory is presented. Furthermore, the study analyses the specific requirements of the process and the workpiece. Later, the design of the developed fixture is methodically given with respect to existing theory of Affordable Reconfigurable Tooling (ART) fixture types and its relevant criteria.

*Experiments/Demonstrators*

The publication demonstrates the implementation of ART by means of manual reconfiguration. The demonstrator utilises both modular and reconfigurable fixture elements in the solution; thus, supporting the classification scheme presented in section 2.2.3. The experimentations are conducted based on proof-of-concept trials, meaning that demonstrators are intended to fulfil the requirements of the project. Meanwhile the relevant data for the demonstrations is gathered. The demonstrators are illustrated in figure 14.

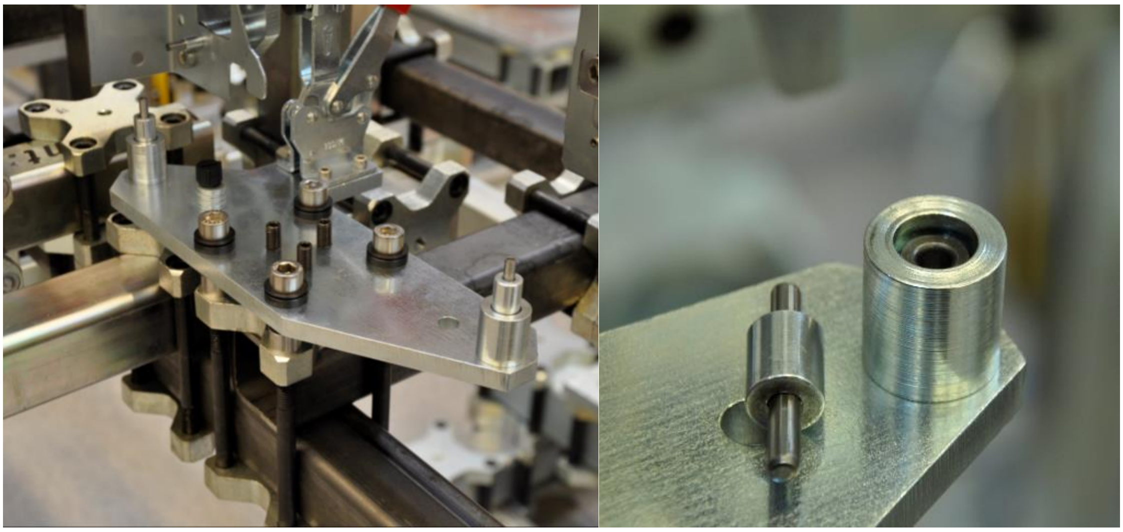


Figure 14. Publication A demonstrators

*Results*

In the context of this study, this publication aims to answer the first research question. The criteria identified and used based on existing theory and experimentations are:

- **Stiffness**: Capability of a fixture to remain within a specified range of deflection under specific loads
- **Accuracy:** The fixture locators' accurate positioning relative to a given coordinate frame
- **Repeatability:** The fixture's ability to locate the workpiece within a specified range of deviation
- **Flexibility:** The fixture's ability to be reconfigured in terms of total number of DOF.

- **Reconfiguration Time:** The total amount of time required for reconfiguration
- **Design and Deployment Time:** The total amount of time spent on design and installation of the fixture solution
- **Capital Cost:** Investment cost required for the fixturing solution

Even though Publication A is not intended to answer the second research question, it also demonstrates the methodical development of ART fixtures.

*Conclusions*

The conclusions drawn by Publication A support the research clarification by means of pointing out the three aspects specified in section 3.2. Furthermore, the criteria used do indeed facilitate the creation of a flexible fixture solution. However, when designing flexible fixtures a broader approach needs to be included early in the design phase, as certain aspects of the utilized fixture theory led to somewhat inapt solutions. Therefore, in order for the theory and results of the implementation to be coherent, the true nature of trade-offs in terms of efficiency need to be ascertained.

## 4.3 PUBLICATION B

***Development of Automated Flexible Tooling as Enabler in Wing Box Assembly***

*Description*

This publication is based on the hexapod development study conducted in conjunction with assembly requirements for the aerospace industry. The study in this the publication discloses the preliminary results on the development of a hexapod designed to act not only as a fixture body but also as an assembly robot. The publication also addresses the utilisation of sensor information to provide adaptive assembly of a compliant rib into a wing-box.

*Aim*

The publication's aim is to offer an approach on fixture design and preliminary results based on the specific and general requirements on fixturing solutions for the aerospace industry.

*Research Approach and Utilised Fixture Theory*

The publication initially offers a literature review and utilises the findings in order to build a theoretical framework for the methodical approach. Similar to Publication A, this publication also presents detailed information regarding the development process within the framework of a methodical approach.

*Experiments/Demonstrators*

The development of the hexapod was carried out in a laboratory environment with controlled variables. The demonstrator is comprised of a modular and reconfigurable fixture in conjunction with the classification scheme presented in section 2.2.3. The experiments are carried out by emulating the process requirements. Furthermore, the experiments on force feedback assembly are analysed. The experimental set-up and relevant assembly process is illustrated in figure 15.

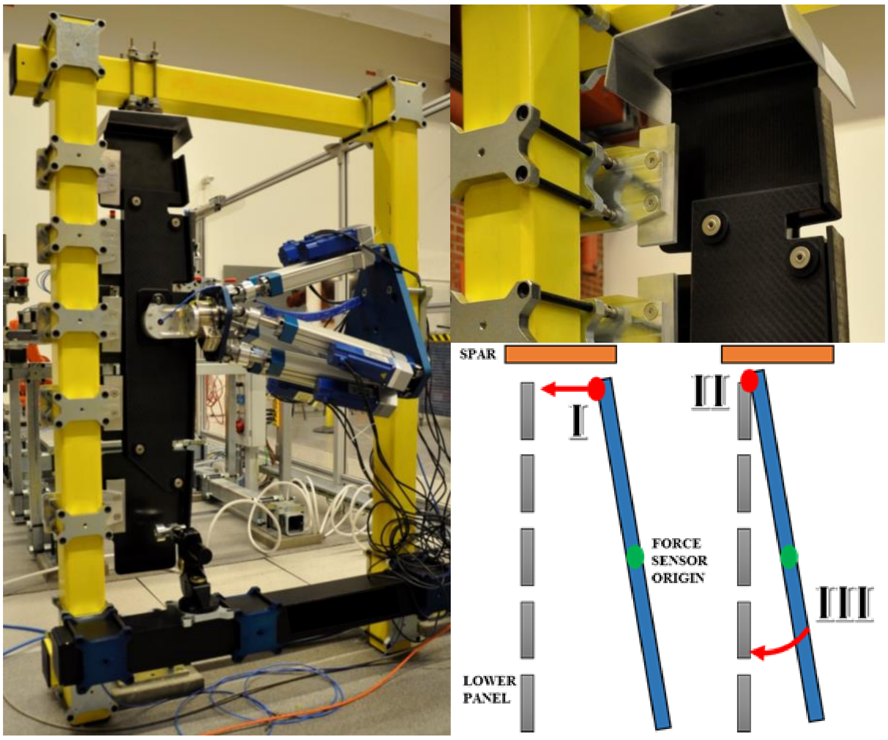



Figure 15. Hexapod demonstrator and force feedback assembly experimental approach

*Results*

In order to illustrate the approach taken, the publication provides the investigation of manufacturing systems with a particular focus on RMS and AMS. Based on the characteristics of the aforementioned manufacturing paradigms, the publication describes the implementation of these characteristics in conjunction with section 2.6. These characteristics are mainly grouped according to *automation capability*, *utilisation of measurement systems*, *level of intelligence in terms of sensor support* and *control system capabilities*. Furthermore, the approach gives a breakdown of a reconfigurable fixture with respect to individual groups categorised as *mechanical design*, *controller design* and *software development*. Therefore, the particular approach contributes to research clarification and enhances understanding.

In addition to the criteria identified in Publication A, the results of the analysis determine the following criteria that play an important role in reconfigurable fixture development

- **Reusability:** Capability of a reconfigurable fixture to be used for different processes
- **Quality:** Capability of a fixture to handle process variation
- **Maintenance Load:** Time and cost impact of a malfunctioning reconfigurable fixture on a production system
- **Process integration:** Capability of a reconfigurable fixture to integrate with other manufacturing technologies
- **Scalability & Standardisation:** The capability of fixture to use standardised components
- **Procurement Time:** The maximum lead time required for the standard components

Due to the preliminary state of the publication, the numerical results of the measured criteria are not disclosed in this publication. However, it is confirmed that each feature added to reconfigurable fixtures, such as automation and activeness, increases the complexity for determining efficiency. In a laboratory setting, the criteria were observed to be satisfied by the initial requirements prescribing a solution.

In summary, this publication contributes to the answer to *RQ 1* by adding to the criteria presented by Publication A. Furthermore, the publication discloses the different utilisation requirements and characteristics that can build an initial frame for the *RQ 2*.

*Conclusions*

The publication's results clearly show that the individual characteristics of a fixture solution and the specific manufacturing system require to be harmonised in order to achieve an efficient fixture solution. This harmonisation can subsequently be used to describe and implement efficiency in a fixturing solution.

## 4.4 PUBLICATION C

***Automated Flexible Tooling for Wing Box Assembly: Hexapod Development Study***

*Description*

This publication describes the collaborative efforts towards reconfigurable fixture development in the LOCOMACHS project. Where this publication differs from Publication B is that the development and experimental data captures the complete span of aerospace assembly fixtures. Furthermore, the publication provides detailed methodological descriptions of reconfigurable fixtures and analysed data regarding the outcome of the measured criteria.

*Aim*

The particular purpose of this publication is to demonstrate the enabling synthesis of reconfigurable fixtures and new build philosophies driven by manufacturing paradigms.

*Research Approach and Utilised Fixture Theory*

The publication initially offers a minor literature review of the scholarly work conducted in the field. Secondly, an analysis of the new build philosophy and manufacturing paradigm is conducted with respect to the existing body of knowledge based on the conclusions of Publications A and B. Thirdly, the publication describes the methodical development of suggested solutions and the experimental procedure. Finally, experiments are carried out in order to identify the fitness of the developed solutions.

*Experiments/Demonstrators*

The full-scale integration of developed reconfigurable fixtures in a semi-controlled environment is described. The demonstrators are built at an emulated manufacturing site at the Manufacturing Technology Centre (MTC) in Coventry, United Kingdom. The experiments are conducted with the aid of measurement system with laser tracking technology during complete wing box loading. The demonstrator and experiments are illustrated in figure 16.

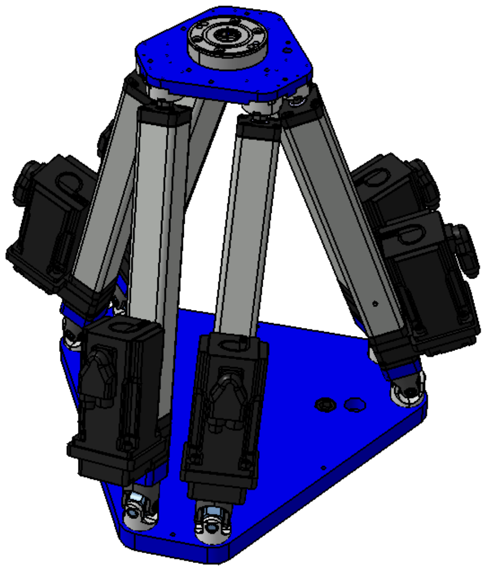
*Results*

The results presented in this publication focus on providing answers to both research questions. After analysis of the literature, specific process, workpiece and manufacturing system, the following criteria were formulated to contribute to answering *RQ 1*. The specified criteria are *stiffness*, *accuracy*, *repeatability*, *flexibility*, *workspace*, *cost* and *procurement time*. As it can be seen from the criteria, the extended integration and experiments have resulted in the same criteria as the established theory as stated in the previous publications. On the other hand, the broader scale of application revealed noticeably different expectations on the controller and software development. When further analyses are conducted, the differences in the practice of fixture design are categorised with respect to the following characteristics

- **Robotics capabilities:** The fixtures capability to conduct online and offline programming, coordinate frame adaptation and rapid error handling. This characteristic is formulated in order to enable the execution of automated reconfigurable fixtures during set-up and planning operations.
- **Controller independency:** The capability of controller to be reused for various types of fixturing solutions. This characteristic is utilised in order to correlate to the capital cost requirement where the cost of multiple controller for each reconfigurable fixture surpassed the threshold set by the metrics specified.
- **Effective calibration:** The capability of a reconfigurable fixture calibrate itself automatically without the aid of an external metrology tool. This characteristic is identified as essential in automated fixturing solutions, as the use of external calibration equipment such as metrology systems is found to increase the set-up cost and time for automated fixtures.
- **Knowledge demand:** The capability of the developed fixture solution to be rapidly learned. This particular characteristic is observed to have an impact on the applicability of a fixturing solution due to the introduction of robotics-related functionalities.


Figure 16. Experiment and demonstration site at MTC

This publication also elaborates on the foundation for answering *RQ 2* provided by Publication B. For reconfigurable fixtures, the publication provides answers on how to utilise the kinematic structure information in a methodical manner. The process of design is initially dived into three distinct categories of mechanical, control and software. In mechanical design, the process is initiated with the selection of kinematic structure. After the determination of the kinematic structure, the custom and standard components are allocated to the relevant pieces. Therefore, the publication demonstrates how the kinematic coupling can be utilised to configure and allow various types of reconfigurable fixtures with respect to different requirements. The outcome of configuration is illustrated by figure 17.



| Choice | Part selection | Standard part (yes/no) | Choice 1 | Choice 2 | Choice i |
|---|---|---|---|---|---|
| 1 | Actuator Brand/Model | yes | A | B | Xi |
| 2 | Actuator Modular size | Range | Small | Medium | Large |
| 3 | Stroke length | yes | 100 | xx | 500 |
| 4 | Motor Brand/Model | yes | A | B | Xi |
| 5 | Motor size and power | Range | Low torque | Medium torque | Heigh torque |
| 6 | Base Joint Type | yes | BallJoint | Universi al Joint | |
| 7 | Base Joint Size | Range | Small | Medium | Large |
| 8 | Base Plate Shape | No | Thickness, Joint position, features etc. | | |
| 9 | Base Plate Material | n/a | Steel | Aluminium | Carbon Fibre |
| 10 | Top Joint Type | yes | BallJoint | RRR Joint | |
| 11 | Top Joint Size | Range | Small | Medium | Large |
| 12 | To Plate Shape | No | Thickness, Joint position, features etc. | | |
| 13 | Top Plate Material | n/a | Steel | Aluminium | Carbon Fibre |
| 14 | Locking Typ | n/a | Motor Brake | ETP | |
| 15 | Pickup Typ | yes | Zero point | capto | Force sensor |
| 16 | Colour | n/a | | | |

Figure 17. Example design matrix for a reconfigurable fixture coupled to a hexapod kinematic structure.

In addition to mechanical design, this publication also provides methodical development for controllers. The main components of controllers are identified as drive, motors, Programmable Logic Controller (PLC) or industrial computer and safety systems. Furthermore, the classification and use of standardised components in a controller is found to be an effective tool in terms of corresponding to controller independency. The only constraining functionality was found with the coupling of the motors and drives, which only allowed for the exchange of motors or drives of the same brand. By following the methodical development of controllers, the different configurations of reconfigurable fixtures was complemented. This functionality is illustrated in figure 18.

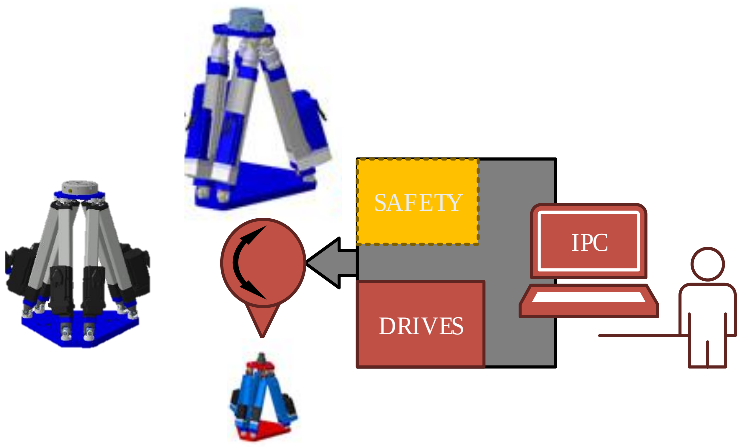



Figure 18. Control system mapping and switching functionality of mechanical configuration

For software design methods for reconfigurable fixtures, this publication offers three families of functions. The first family focuses on the process related functions described as self-guidance, calibration and communication. In the second family focusing on fixturing functionalities, the functions are described as rapid turn on/off of a reconfigurable fixture without data loss and sensor utilisation for process improvements. After describing the important components of an automated reconfigurable fixture software, the publication offers solutions as shown in table 3. Consequently, the publication demonstrates the application of these solutions and establishes benchmark values for the pertinent criteria in the study.

*Conclusions*

The study conducted in Publication D showed that identifying the requirements of a manufacturing system is an important stepping-stone to increasing the efficiency of reconfigurable fixtures. Moreover, the same methodical approach allows the designers to understand and evaluate the cost, time and quality requirements in conceptual level; thus, identified as contributor to the efficiency of the fixture. This means that by coupling functions and characteristics in conceptual design level, the understanding of the process requirements can be easily reflected into reconfigurable fixtures.

Table 3. Identified software functions and suggested solutions

| *Function Family* | *Function* | *Suggested Solution* |
|---|---|---|
| Process Related Functions | Decrease the knowledge requirement to execute the hexapod | Self-guiding execution after activation |
| | Enable independent execution of hexapod from external equipment | Calibration by internal mechanical limits |
| | Facilitate connection to other types of hexapods | Quickly modified kinematics |
| Fixturing Related Functions | Quick on/off for a period of time while maintaining cost effectiveness | Quickly wake-up functionality |
| | Support evaluation/modification of the force feedback | Interface for alter thresholds for safety and clamping |
| Robotics Related Functions | Facilitate online path planning | Jogging functionality in 6-DOFs with rapid code generation |
| | Enable offline programming | Standardized offline programming language |
| | Facilitate working in different coordinate systems | An interface for offset definition |
| | Quick error handling | Interface for track or reset errors on motors and drives |

## 4.5 PUBLICATION D

***A Novel Comparative Design Procedure for Reconfigurable Assembly Fixtures***

*Description*

Publication D offers a comparative design procedure for assembly fixtures. The focus of the publication is on aerospace and automotive industries. The publication presents the development of fixturing criteria with metrics and detailed guide for fixture designers that can be utilised to compare, evaluate and implement numerous reconfigurable fixtures in assembly processes.

*Aim*

The overall aim of this publication is to contribute to the existing theory of fixture design by combining the results of publications A, B and C. Moreover, this publication's aim is similar to that of this thesis – corresponding to the reference model specified by DRM in stage *DS I*.

*Research Approach and Utilised Fixture Theory*

The research approach of this publication is mainly guided by research questions formulated as follows:

- *What parameters can be used as means of input to design and verification aspects of reconfigurable fixtures?*
- *How can these parameters be integrated and utilized systematically to design reconfigurable fixtures?*

Since the aim of this publication is mainly to develop the reference model, publication D asks research questions very similar to the ones of this thesis. The difference of these research questions, on the other hand, is that the claim of the publication is only to establish a guideline to describe efficiency.

To answer the research questions, the utilised knowledge is expanded by a conceptual framework within which the publication investigates criteria from literature on not only fixturing but also manufacturing paradigms. The publication subsequently formulates equations based on the findings to offer metrics for the established criteria. Furthermore, a comparative design procedure utilising these metrics is proposed. Finally, an experimental study is conducted to verify the results.

*Results*

The publication answers *RQ 1* by identifying relevant aspects of manufacturing paradigms. By drawing an analogy with PMS, the publication first presents parameters of *cost, time, quality* and *flexibility* to frame the criteria. These parameters are general performance indicators defined as

- **Cost**: Sum of capital and recursive costs of a fixture
- **Time**: Expense in time for halt of a manufacturing process caused by fixtures
- **Quality**: Robustness of a fixture in relation to the requirements of a manufacturing process
- **Flexibility**: Capability of a fixture to be used for different products and processes

The publication then presents the metrics based on the criteria identified in this frame. For the *flexibility* parameter, the metrics of *reconfigurability, reusability* and *modularity* are proposed. The metrics used to define the *cost* parameter are *investment cost* and *set-up cost*. Moreover, the *time* parameter is defined by *set-up time*. Finally, the *quality* parameter is defined by *diagnosability, reliability* and *convertibility* metrics. The definition of metrics for each parameter is presented in table 4.

Table 4. Fixture efficiency parameters and metrics

| *Parameters/Metrics* | *Definition* |
|---|---|
| **Flexibility** | **Ability of a fixture to satisfy to different products and processes** |
| Reconfigurability | Ability to satisfy products within a product family |
| Reusability | The amount of processes which the fixture can satisfy |
| Modularity | Ability of a fixture to be rebuilt for other processes |
| **Cost** | **Sum of costs as capital and recurring** |
| Investment Cost | Hardware acquisition and software development costs |
| Set-up Cost | The investment required for set-ups in terms of hardware and software |
| **Time** | **Expense in time for halt of a manufacturing process caused by fixtures** |
| Set-up Time | The amount of time to conduct a set-up |
| **Quality** | **Parametrized robustness of a process** |
| Diagnosability | Ability to exchange information, such as accuracy, workpiece deformation and. |
| Reliability | Total standard component-reliability of a fixture |
| Convertibility | Ability to be equipped with external equipment |

In addition to providing metrics, the publication emphasises the importance of the adaptation of metrics into meaningful design constraints. Therefore, for each metric a conversion process is implemented. The outcome of this process results in eight equations illustrated in table 5.

Table 5. Definitions of metrics as efficiency and corresponding equations

| *Metric* | *Definition* | *Efficiency Equation* ($\varepsilon_i$) |
|---|---|---|
| Weight | $W_c$, $W_a$, $W_T$ are the weight efficiency, achieved and target weights respectively. | $W_c = 1 - \frac{W_a}{W_T}$ |
| Dimensions | $V_c$, $V_a$, $V_T$ are volume efficiency, achieved and target volume of the fixturing solutions. | $V_c = 1 - \frac{V_a - V_T}{V_T}$ |
| Reconfigurability | $R_c$ is the ratio of reconfigurability level, $P_T$ and $P_a$ are the number of total products in a family and the products within the feasible workspace of a reconfigurable fixture respectively. | $Rc_c = \frac{P_a}{P_T}$ |
| Reusability | $Re_c$ is the ratio of reusability, $Pr_T$ and $P_{ra}$ are the number of targeted and satisfied processes respectively. Satisfied processes are determined by fixturing parameters of stiffness, accuracy and repeatability. | $Ru_c = \frac{Pr_a}{Pr_T}$ |
| Modularity | $M_c$ is modularity efficiency as the ratio of number of standard components to $N_s$ total number of components $N_T$ | $M_c = \frac{N_s}{N_T}$ |
| Cost | $C_f$ and $C_e$ are the capital costs of a fixture and the set-up cost of external equipment respectively. $C_s$ and $C_T$ are the software and total cost. $C_{wh}$ and $T_A$ are cost per work-hour and allocated effort time | $C_c = 1 - \frac{C_f + C_e + C_s}{C_T}$ $(C_s = C_{wh}T_A)$ |
| Time | $T_c$ is the ratio of time saved to the total time threshold where $T_s$ is set-up time for the respective flexible fixture. | $T_c = 1 - \frac{T_s}{T_t}$ |
| Diagnosability | Binary value that corresponds to the capability of fixture feedback on the workpiece | $D_c = 1$ or $0$ |

| | | |
|---|---|---|
| Reliability | $Re_i$ is the reliability of each standard component in the system and $Re_t$ is the expected threshold | $Re_c = \frac{\prod_i Re_i}{Re_t}$ |
| Convertibility | Binary value representing convertibility requirement | $Co_c = 1 \text{ or } 0$ |
| *Final Efficiency* | *The weight-based distribution of the parameters with respect to production or manufacturing system characteristics* | $\varepsilon_o = \frac{\sum_i^{10} \varepsilon_i w_i}{\sum w_i}$ |

In addition to the metrics presented, Publication D provides a comparative design procedure. This procedure offers a mature answer to *RQ 2* and represents the reference model required in *Descriptive Study I*. In conjunction with the results of previous publications, the procedure divides the process of design into four stages. In the first stage, the conceptual design of a reconfigurable fixture is achieved. By means of evaluating various design solutions, a conceptual verification stage is initiated based on the final efficiency figure. The outcome of the procedure is later carried forward into third stage where the detailed design of the fixturing device is conducted. With a final evaluation and determination of efficiency, the publication offers a complete map of the fixturing device. The proposed procedure (or the so-called *reference model*) is illustrated in figure 19.

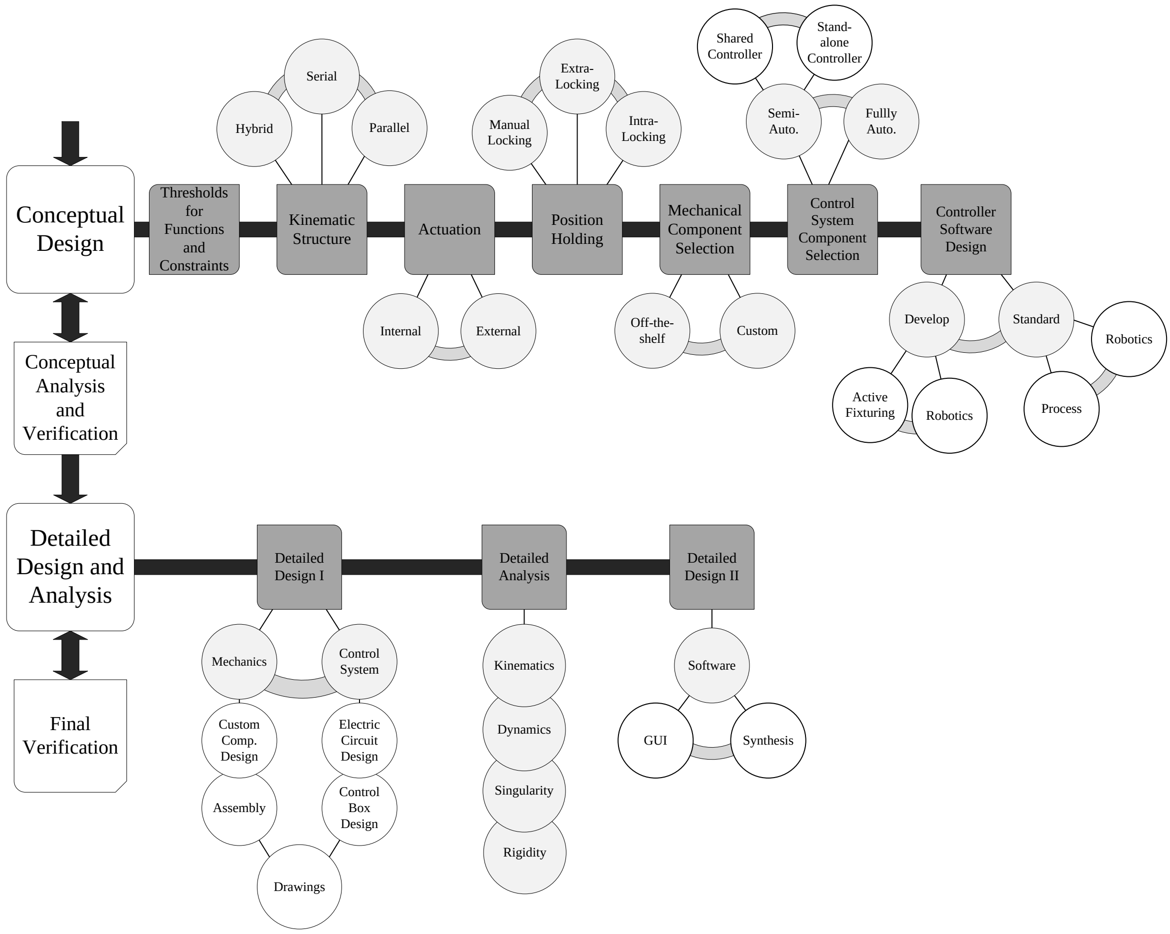



Figure 19. The proposed design procedure integrating metrics and efficiency in four stages

*Experiments/Demonstrators*

The publication verifies the functionality of the design procedure and metrics by means of experiments. The experiments conducted in this publication are reused from Publication A but with the new aim of automating the reconfiguration process. As experiments, the publication utilises two fixturing concepts with different kinematic structures, namely a cartesian and tripod. Initially, the experimental thresholds are converted to metrics and three production system characteristics are identified in terms of weights. Later, the analysis is conducted for both kinematic structures as shown in table 6 and figure 20. Moreover, efficiency values are computed and the detailed design of the Cartesian structure is completed based on the efficiency values. Finally, a demonstrator is used to validate the functionality of the procedure as shown in figure 21.

*Conclusions*

This publication draws the conclusion that by enabling the comparative evaluation of reconfigurable fixtures, designers can be helped to reach conclusions when choosing between various solutions early in the design stage. Furthermore, such procedure also enables the designers to trace the root causes of inefficiency and take corrective measures to increase the absolute efficiency.

Table 6. Experimental thresholds and production system characteristics reflected as weights

| *Parameter* | *Limit* | *Prod. Sys. 1* | *Prod. Sys. 2* | *Prod. Sys. 3* | *Cartesian* | | *Tripod* | |
|---|---|---|---|---|---|---|---|---|
| | | | | | *Achieved* | *Metric* | *Achieved* | *Metric* |
| Weight $(W_a)$ | 5 kg | 10 | 10 | 10 | 8.457 kg | 0.15 | 2.29 kg | 0.77 |
| Volume $(V_d)$ | 27 l | 10 | 10 | 10 | 8 l | 0.70 | 26 l | 0.04 |
| Reconfigurability $(P_t)$ | 4 | 20 | 20 | 30 | 8 | 0.8 | 10 | 1 |
| Reusability $(P_r)$ | 4 | 10 | 15 | 15 | 4 | 1 | 4 | 1 |
| Cost $(C)$ | 100$ | 54 | 30 | 70 | 55.45 $ (St.=11.54+ Custom=34+ Soft.=10) | 0.44 | 42.2$ (St.=18.4 + Custom=29 + Soft.=10) | 0.43 |
| Time $(T_t)$ | 60 s | 54 | 88 | 30 | 20.5 sec | 0.66 | 50.5 sec | 0.16 |
| Diagnosability $(D_c)$ | N/A | 1 | 1 | 1 | 0 | 0 | 0 | 0 |
| Reliability $(Re_t)$ | 0.99 | 20 | 10 | 20 | 0.7 | 0.70 | 0.96 | 0.96 |
| Convert. $(Co_c)$ | N/A | 1 | 1 | 1 | 0 | 0 | 0 | 0 |
| Modularity $(M_c)$ | 0.8 | 20 | 5 | 13 | $N_s$ =14 $N_T$ =24 | 0.64 | $N_s$ =45 $N_T$ =62 | 0.88 |

| ***Final Efficiency*** | Cartesian | | | Tripod | | |
|---|---|---|---|---|---|---|
| | *Prod. Sys 1* | *Prod. Sys 2* | *Prod. Sys 3* | *Prod. Sys 1* | *Prod. Sys 2* | *Prod. Sys 3* |
| | **0.60** | **0.64** | **0.60** | **0.54** | **0.46** | **0.63** |

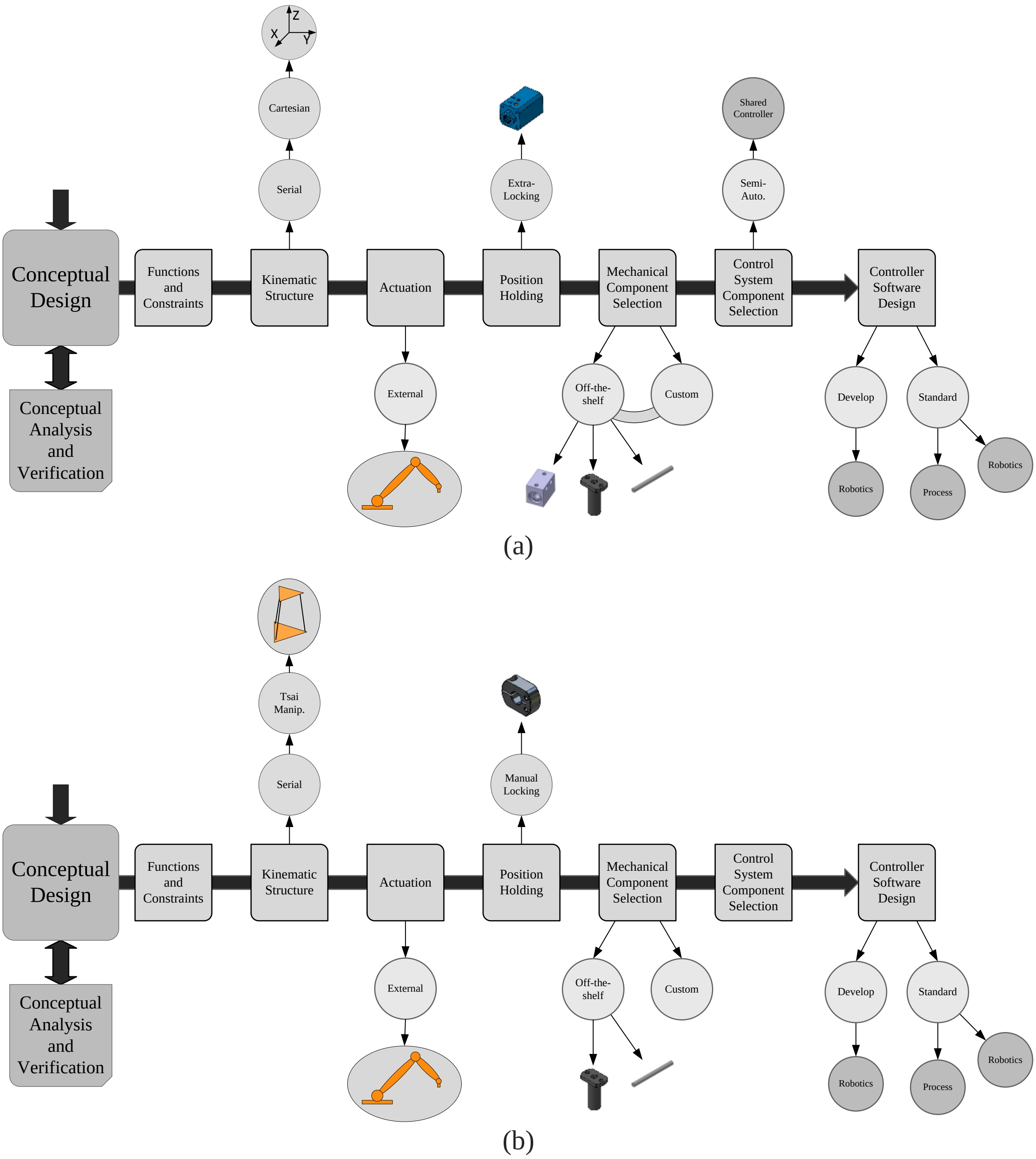
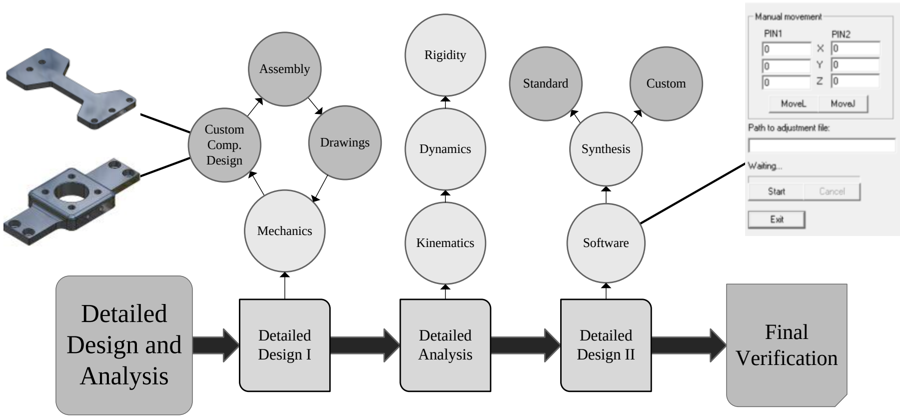
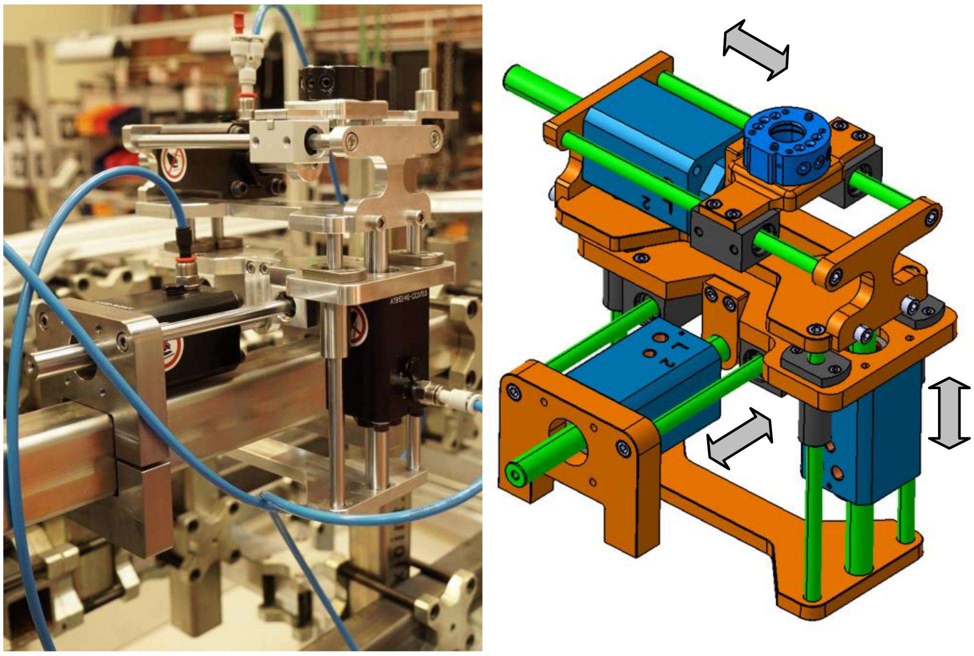



Figure 20. Comparative design procedure for (a) Cartesian and (b) tripod structures




(a)



(b)

Figure 21. Cartesian reconfigurable fixture (a) detailed design stage (b) implemented solution

## 4.6 SUMMARY OF RESULTS

Throughout this chapter, the results of the publications are described with respect to not only knowledge flow but also chronology. In this context, Publication A focuses on applying the existing technology with manual reconfiguration to the automotive industry. It utilises the theoretical knowledge with fundamental fixturing criteria. In conclusion, it emphasises that the application of existing flexible fixturing technologies relies on a wider perspective than simply the limited criteria suggested by existing theory. Publication B utilises the criteria and the conclusion drawn by Publication A and extends the perspective to a manufacturing-system level. Moreover, Publication B also changes the area of application to the aerospace industry and automated reconfigurable fixtures. Furthermore, this publication offers six additional criteria and a basic framework for flexible fixture design. Consequently, these two publications clarify research goal and develop an understanding of the fixture efficiency.

Publication C offers an extensive study on the development of reconfigurable fixtures. Four additional criteria were utilised. Furthermore, the publication offers a methodical product development approach by identifying the elements of a reconfigurable fixture from mechanical, control and software perspectives. In addition, Publication D encapsulates the previously determined criteria and identifies the pertinent metrics. Moreover, the publication offers a formal design procedure that enables a fixture designer to understand how individual choices affect the individual metrics and efficiency of a reconfigurable fixture. Consequently, Publications C and D aim to develop a reference model and answer both research questions. The evolution of the answers to the research questions is illustrated in figure 22.

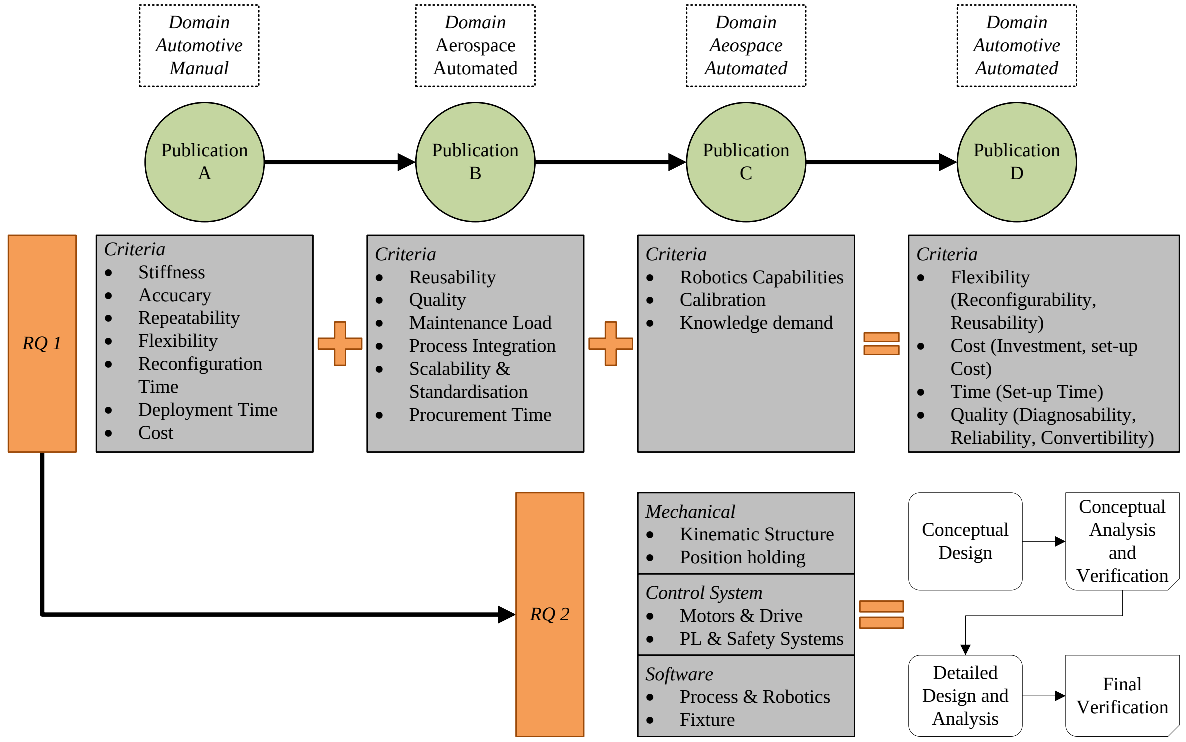



Figure 22. Summary of results with respect *RQ*s: Criteria, metrics and procedure

# V

# DISCUSSION

This chapter aims to answer the research questions and provide an evaluation of the conducted studies with respect to the overall research approach.

## 5.1 ANSWERING RESEARCH QUESTIONS

***RQ 1)*** **What are the criteria that can be used to describe the efficiency of flexible fixtures?**

The industry-standard approach to the design and evaluation of the technological capabilities of fixtures relies on six major aspects: Stiffness, Accuracy, Repeatability, Weight, Dimensions and Cost. Stiffness, as the most fundamental criterion, describes the capability of the fixture to withstand process forces within an acceptable range. Accuracy and repeatability describe how correctly and repetitively a workpiece can be located. Moreover, the weight and dimensional restrictions are applied on the fixture so that the process can be executed from an accessibility perspective. Finally, the proposed solution is evaluated with respect to thresholds related to capital and recurring costs. The important understanding gained about these fundamental criteria is that they are highly correlated to a particular process and workpiece. Therefore, this proposition evolved from the general fixturing theory and practice holds true for fixtures of a dedicated nature. On the other hand, complications emerge regarding the utilisation of these criteria as the concept of flexibility is implemented in fixturing devices. As more effort is channelled towards the use of flexible fixtures, the more apparent the disconnect between technological capabilities and performance becomes.

When the nature of this disconnect is scrutinised, the source of the conflict stems from the fact that the criteria for fixture design are individually analysed and flexible fixture solutions are implemented accordingly. An example of this is described in Publication A. In order to reduce the cost, the nature of fixture reconfiguration is reduced to manual work. Even though such solution leads to lesser capital and recurring costs, the expenditure in time to reconfigure the fixture contradicts the very nature of a highly-automated production line. However, a cross-criteria approach in Publications B and C where fully automated fixturing solutions are implemented in the manual work-oriented aerospace industry shows that the efficiency of a flexible fixture relies on understanding the needs of a manufacturing system and designing accordingly. Consequently, the criteria for efficiency should not be seen from a single point of view as with the existing theory, but rather try to capture the performance of a flexible fixture from a manufacturing system's perspective by merging technological and performance perspectives.

In section 3.2, the efficiency of a fixture is identified from three perspectives. In light of the existing theory, the first perspective – technological capabilities of a fixture – is described by how stiff, accurate and repeatable a fixture is within the specified dimensional and weight limits. As it is found that these criteria are correlated to the individual requirements of a workpiece and process (Publications A, B and C), extending the criteria to the fitness of a flexible fixture for multiple workpieces and processes can be used to describe the technological capability of flexible fixtures. Therefore, the pertinent criterion and its expected state are proposed to be the following:

***Criterion I*** ***A flexible fixture's physical capability to satisfy circumscribed workpiece and process requirements is a factor of flexible fixturing efficiency.***

***Expected state****: A flexible fixture must be physically capable of satisfying circumscribed workpiece and process requirements.*

The technological capability of a fixture to contribute to process quality can be realised by the same technology that allows its flexibility. Therefore, the activeness of a flexible fixture is an important aspect that surpasses the fundamentals of a fixture as a locating and securing tool to make it an active contributor that adds value to the workpiece (Publications A and B). Consequently, the criterion and the relevant expected state regarding the relationship between a flexible fixture and quality is proposed as following:

***Criterion II*** ***Contribution to process quality is an element of flexible fixture efficiency.***

***Expected state****: A flexible fixture should contribute to process quality.*

As a technological capability, the manipulation of a flexible fixture, regardless of its physical form, requires precision in order to remain within the requirements of a workpiece and/or process. Whether this precision takes the form of metrological input or assembly sequence, this demand drives fixtures to interact with manufacturing resources spanning from humans to other machines. Subsequently, a flexible fixture with the same capability is found to contribute to efficiency (Publications A and C); thus, *Criterion III* and the expected state are formulated as following:

***Criterion III*** ***Interaction capability with other resources in a manufacturing cell, production or manufacturing system influences flexible fixturing efficiency.***

***Expected state****: A flexible fixture should be able to interact with other resources in a manufacturing cell, production or manufacturing system.*

Due to the fact that flexibility by means of reconfiguration or rebuilding is inherently implemented in a flexible fixture, the features to achieve flexibility affect both technological capability and performance perspectives. Therefore, the expenditure in time required for a flexible fixture's adaptation to multiple workpieces and processes should be on a reasonable level determined by the needs of a specific manufacturing system. Subsequently, *Criterion IV* and its expected state are proposed:

***Criterion IV*** ***The time to reconfigure and/or rebuild a flexible fixture affects flexible fixturing efficiency.***

***Expected state****: A flexible fixture should be rapidly reconfigured and/or rebuilt.*

Similar to the time aspect of flexible fixtures, their scalability and ease-of-maintenance is also at the crossroads of technological and performance perspectives. Specifically, a flexible fixture's level of modularisation is an important factor for scalability and ease of maintenance. The majority of the literature – particularly that related to modular fixtures – emphasises the fact that the use of standardised components is the enabling feature for modularity (section 2.2). Hence, the more the fixture is designed using standard components, the easier scaling becomes within the dimensional limits of the standard components (Publication C). As a result, *Criterion V* and the relevant expected state are formulated as:

***Criterion V*** ***Modularisation using standardised components effects the efficiency of flexible fixtures.***

***Expected state****: A flexible fixture should be modularised using standardised components.*

With a specific focus on the performance of a flexible fixture, cost is of great importance. In order for a flexible fixture to remain competitive, the capital expenses required for the fixture body and its operations should be carefully scrutinised with respect to the needs of a manufacturing system. Specifically, it is found that the cost of a fixture should not be evaluated as an absolute value but a relative one to existing solutions. This means that each manufacturing system has a unique expectation on the flexible fixture. Thus, the justification for using a flexible fixture can only be assessed when a comparison is made with the existing fixture that the flexible fixtures are intended to replace. Consequently, *Criterion VI* and its expected state are proposed as following:

***Criterion VI*** ***A flexible fixture's efficiency is influenced by the capital cost of the fixture and relevant operations.***

***Expected state****: A flexible fixture's total cost should remain competitive against existing solutions.*

In order to utilise the capability of a flexible fixture over the long term, the reliability aspect must be considered when describing the efficiency of a flexible fixture. It is found in Publication C that flexible fixtures are more prone to malfunction than dedicated fixtures, as the number of components increases with flexibility. A robust, low-maintenance fixture ensures the continuity of the process and, thus, remains competitive against dedicated counterparts. Hence, *Criterion VII* and the pertinent expected state are formulated as following:

***Criterion VII*** ***Maintenance of a flexible fixture is an aspect to consider in terms of flexible fixturing efficiency.***

***Expected state****: A flexible fixture should be robust and minimally prone to malfunction.*

An important aspect of efficiency relies on the quantification of the aforementioned criteria. In section 2.5 and Publication D, the concept of efficiency is found to be correlated to the hierarchical approach that PMS offers. In conjunction with PMS, Publication D offers metrics that quantify how each criterion is fulfilled from *cost*, *time*, *quality* and *flexibility* perspectives. In the flexibility parameter, the first metric – *reconfigurability* – aims to measure the number of products within the workspace that can be accommodated by a flexible fixture in conjunction with *Criterion I*. The second metric, *reusability*, quantifies the number of processes for which the flexible fixture can be utilised where this metric uses the information related to stiffness, accuracy and repeatability. In addition to reconfigurability, reusability also contributes to *Criterion I*. Furthermore, physical restrictions are also identified by the process requirements. The metrics that quantify these restrictions are offered as *weight* and *dimensions*. The final metric for flexibility, *modularity*, is measured to quantify the capability of a fixture to be modularly rearranged for different processes. This metric is proposed in correlation to *Criterion V*.

Secondly, the cost parameter aims to quantify *Criterion VI*. The cost efficiency of a fixture is measured by the metrics *investment cost* and *set-up cost*. The investment cost represents the total capital cost of a fixture in terms of hardware and software. The set-up cost is the metric that quantifies the financial aspect of an investment for any external equipment required to operate the fixture. Thirdly, the time parameter represents *Criterion IV*. For this parameter, a flexible fixture's *set-up time* is proposed as a metric defined by the total amount of time from the stop of a process until the process is restarted. For the quality parameter, three metrics – *diagnosability*, *reliability* and *convertibility* – are proposed. The diagnosability of a flexible fixture measures the capability to give/receive feedback on the process in conjunction with *Criterion II*. Moreover, the reliability of a fixture quantifies the total reliability of a flexible fixture by considering the individual reliability value of each standard component. The reliability metric aims to quantify *Criterion VII*. Finally, convertibility of a fixture quantifies the capability of a fixture to mount/remove or interact with external resources used in a manufacturing process where the convertibility metric is correlated to *Criterion III*.

As an input to *RQ 2*, the efficiency of a flexible fixture is heavily dependent on how it reflects manufacturing-system requirements. The conditions of the environment in which the flexible fixture is intended to perform determine its efficiency. These conditions are, as in conjunction with the performance measurement systems, related to short- and long-term impacts within the framework of cost, time, quality and flexibility.

***RQ 2)*** **How can these criteria be methodically used in the design of flexible fixturing solutions to increase their efficiency?**

The methodical inclusion of criteria metrics into flexible fixture design is essential in providing an answer to this research question. When the aforementioned criteria and their relevant metrics were utilised, it was found that these metrics conflict with one other. As the fixture's flexibility increases, the cost-efficiency is conversely affected. Another example is the decline of time-efficiency in order to compensate for the cost-efficiency by removing automation features. Within this field of trade-offs, one particular question underlies the methodical inclusion – "*Which of the criteria should be prioritised in order to increase the efficiency of flexible fixtures?*" As pointed out in Publications B, C and D, absolute values do not exist for flexible fixtures for the criteria given in *RQ 1*, clearly advocating the adaptation of flexible fixtures with respect to the individual needs of a manufacturing system. In correlation to the field of trade-offs, it is found that a weighting function aiming at finding the weighted mean of all criteria metrics can provide a final efficiency value (Publication D, see table 5). Consequently, the efficiency shaped by the requirements of the unique nature of a manufacturing system can drive the fixture design process to focus not only on critical aspects but also on the wider issues.

In addition to the weighted distribution of metrics, another important characteristic that requires consideration is the utilisation of the efficiency value. Due to the fact that efficiency is far from an absolute, the comparative use of efficiency values between individual fixture solutions or components embodies the foundation of methodical inclusion of metrics. However, the critical point is to enable the evaluation of efficiency before the detailed design is initiated. As Publications A, B and C show, the early evaluation of a flexible fixture with respect to given requirements is important in achieving robust solutions. Therefore, the efficiency value utilised as a product design constraint on a conceptual level enables an estimation of efficiency before the detailed design of a fixturing solution is initiated. In this way, the selection of the fixture with the highest efficiency is facilitated, also contributing to timesaving on fixture design by omitting the remaining flexible fixture options at the conceptual design phase.

Moving further into the methodical process, a key understanding gained for the complete inclusion of metrics is the need to decouple and systematise the design process. By dividing this process into conceptual and detailed design stages, complemented by an evaluation stage after each, initial decoupling is achieved. The conceptual design stage is distributed over seven steps. In step one, the metrics' threshold values are defined with respect to pertinent workpieces and processes, and the manufacturing-system requirements are identified. In step two, kinematic structure in terms of serial, parallel or hybrid is selected by the fixture designer. In step three, the actuation – internal (i.e. completely automated, reconfigurable fixture) or external (i.e. reconfiguration by an externally available resource such as an articulated robot) – is defined. In step four, the options to evaluate position holding are determined - which are manual (i.e. the locking of the position after reconfiguration is provided by a human), external (i.e. locking is supplied or controlled by an external automation tool) and internal (i.e. the flexible fixture is responsible of holding the position by internal locking technologies) locking.

After selecting the relevant features, another important aspect is to select the individual elements in a flexible fixture. In Publications B and C, the coupling of kinematic structures with components is demonstrated and the importance of parametric design is emphasised. In Publication D, the same aspect is presented as established design knowledge by means of component and assembly libraries. The concept of assembly libraries individualises the design process by allowing the designer to utilise information shaped by experience. This aspect of the individual design is found to be crucial as it supports customisation and adaptation to manufacturing-system requirements, rather than offering a general solution with absolute efficiency. In the light of this knowledge, the position holding step is followed by the mechanical component selection where the components are further divided into categories as off-the-shelf and custom. By using the assembly library, custom and off-the-shelf components are appointed to the kinematic structure. In step six, control components are selected based on the actuation and positon holding type –categorised as semi- or fully-automated. In step seven, controller software design is executed by selecting features from categories of standard (i.e. standard robotics and process features as in Publication C) and develop (i.e. activeness and custom robotics features as in Publications B and C). Finally, the metrics are measured with respect to achieved values and the threshold values specified in step one of conceptual design. At this point, a designer is expected to face two specific situations. In the event that multiple solutions exist, the selection of the solution with the highest efficiency is recommended. If there is only one available solution, then the root cause of inefficiency can be traced back to the individual elements. The efficiency of a single solution can also be successfully increased. The final two stages focus on the detailed design and final evaluation of the selected flexible fixture. In the detailed design stage, the design process is divided into three steps. Firstly, the mechanical and control system design is completed. For mechanical aspects, custom components are designed and assembly is performed. For the control system, the electrical circuits and control box are developed. Secondly, a detailed analysis is conducted with respect to kinematics, dynamics, singularity and stiffness of the flexible fixture. When the detailed analysis yields satisfactory results, the custom software is designed. The final stage is then executed in order to verify the final efficiency of the flexible fixture.

In the execution of this process, it is found that certain metrics need to be estimated in the conceptual design stage; to be later compared to the final efficiency value. In the experiments conducted, it was observed that challenges arise as the investment cost and reusability metrics are estimated. When there is insufficient knowledge regarding the chosen flexible fixture, it is possible that investment costs for custom mechanical and software components may deviate during the detailed design phase. The efficiency deviation after the detailed design phase can therefore be minimised by adopting an axiom that the components satisfying the selected kinematic structure can only be selected from a library of components with proven functionality. The risk of unexpected fixture efficiency results can then be avoided.

## 5.2 EVALUATING RESEARCH APPROACH: VERIFICATION & VALIDATION

The results presented in this thesis correspond to the progress embodying RC and DS *I* phases of Design Research Methodology. Following the steps proposed by DRM, the goals of the research clarification phase are completed; with the frame of research being fully specified. In DS I, all publications aimed to develop an understanding on how the efficiency of a flexible fixture can be presented as a reference model. However, in order to finalise the DS I phase a specific evaluation stage needs to be conducted in addition to the internal and external verifications proposed in section 3.5. In this particular case, the evaluation stage corresponds to the validation of the reference model. Hence, it is crucial to identify the verified results and threats to the validity of this thesis.

### 5.2.1 VERIFICATION

As specified in section 3.5, Buur [132] identifies two aspects of verification; the internal and external. In internal verification, logical reasoning based on *consistency*, *coherence*, *completeness* and *ability to explain unique phenomenon* is pursued. For external verification, the acceptance of the theory and models by experienced users is desirable. In this section, each element of verification will first be described in more detail before an evaluation of the findings is presented.

- *Consistency*: The state of the theory where the pertinent elements remain in agreement to each other.
    - The results obtained and stated in each publication contribute to the existing body of knowledge to be utilised in subsequent publications. As demonstrated in the results section, the iterative nature of theory utilisation enabled new learning and perspectives.
- *Coherence:* The utilisation of theory elements remains in harmony with the results obtained.
    - The experimental nature of the publications by means of demonstrators is based on the practice of the theory and its methodology. The results are coherent as they are intended to demonstrate the efficiency of a flexible fixture.
- *Completeness*: The capability of the developed theory to explain earlier phenomena.
    - As the developed theory is based on the vast range of fixturing paradigms, the application of efficiency is extended to flexible fixtures; with experimentation on different elements of fixturing paradigms. Furthermore, the theory presented in Publication D provides a particularly important stepping-stone to

gaining the relevant capability. Based on the results of earlier publications, the theory is presented with axioms and generalised to cover the various kinematic structures of fixtures.

- *Ability to explain unique phenomenon:* The capability of the theory to explain specific phenomena.
  - Each publication is based on projects that typify the current state of the industry. Therefore, the versatility of individual phenomenon is integrated into the theory.

The external verification of the findings contained in this thesis is limited to the demonstrators in laboratory and field settings, along with the peer review of each publication. Specifically, the demonstrators for each publication were used to demonstrate the critical aspects of efficiency for a panel of experts from a variety of backgrounds. The fitness of the proposed solution in each paper is discussed and evaluated with respect to the stated specifications for each project.

### 5.2.2 VALIDITY: IDENTIFYING & MANAGING THREATS

In conjunction with section 3.5, the four types (*statistical conclusion*, *internal*, *construct* and *external*) of validity proposed by Cook and Campbell [129] are utilised for the evaluation of the findings of this thesis. The motivation behind the approach of this section is based on the argument offered by Maxwell [120] "*The validity of a research is not about how correct it is; but about how wrong it may be."* Thus, the following types of validity are defined and correlated to the findings of this thesis in terms of so-called *threats* for each type of validity. Throughout the identification stage, the deeper analysis of threats in design research presented by Blessing, et al. [128] is also utilised. Furthermore, as the individual publications involve experimental data collection, the arguments regarding *reliability* are presented along with statistical conclusion validity.

***Statistical Conclusion Validity & Reliability***

Statistical conclusion validity represents the covariance of the variables to measure within a study or collection of studies [128]. One of the major aspects of statistical conclusion validity is on the correctness of the measurements. Complementing this aspect with the nature of experimentation, Yin [131] treats the subject of statistical conclusion validity in conjunction with reliability and offers a protocol so that the experiments can be repeated.

In all of the publications, experiments are decoupled from the original design of the utilised company specific workpieces; with relevant input transparently described. The pertinent thresholds of the various metrics are expressed in generalised units meaning that the standards in the available literature are used. The processes and instruments of experimentation are described. Furthermore, all publications are intended to provide characteristic rather than absolute values in order to minimise the threat of unreliable measurements. Moreover, the unique design solutions for all publications have been explained in correlation to the existing theory of kinematics to improve the repeatability of experiments.

***Internal Validity***

Internal validity is the investigation of the causality of the variables in an experimental study. Creswell [123] and Blessing, et al. [128] identify numerous types of threats to this type of validity. In particular, for a study employing experimental data collection on the technological aspects of fixtures, the threats to internal validity are identified as being experimenter effects, measurement, instrumentation and the reliability of pre-tests of selected cases. In order to manage the possible threats resulting from experimenter maturity, two different countermeasures are utilised. First, the individual technological solutions offered in the different publications are not reused, so that the specific biases or maturity of the designer would not affect the next publication. This is an important aspect that enables the designer to experience new technologies and draw conclusions based on novelty rather than so called "*rule of thumb*" approaches.

Secondly, as stated previously, the objective of this thesis is not to derive absolute values for the efficiency of fixtures but rather to deploy methods of relativity. This means that the characteristics derived by Publications A, B and C are evaluated relatively with respect to the existing fixturing solutions. Hence, the existing fixturing solutions become the *control group* (a term mainly utilised by social sciences describing a group of subjects that are not treated by the experiment [122]) with respect to which all the experimental conclusions are drawn. Furthermore, the control group is identified as containing dedicated and/or modular fixtures; thus, the measurements are made relative to the existing solutions using current industry-standard methods and instrumentation (Publication A with measurement arms and/or Publications B and C with laser trackers). Thirdly, all of the experimental input provided by the projects has been in use by the companies in question over a long period of time and repeatedly proven to be functioning for the control group. In addition, the input and control group offer normal characteristics; thereby eliminating regression and building reliability in the pre-tests.

***Construct & External Validity***

Construct validity represents the investigation of the versatility of the results obtained where external validity aims to find the domains/boundaries in which these constructs are valid.

*Constructs and Measures*

Yin [131] manages the threats to construct validity by collecting data from multiple resources and establishing a chain of evidence where Creswell [123] and Maxwell [120] offer the concept of *triangulation* as a means of managing construct validity threats. The seven criteria of efficiency represent the constructs built in Publication D and are based on the output of Publications A, B and C. These constructs have been operationalised in comparison to the control group argued in internal validity. Moreover, the operationalisation of the constructs is realised based on the content of the publication. In all publications, the control group was the dedicated and modular fixtures in target facilities. Each facility was personally visited by the authors of the publications and project content was further established by observations. Later, the observations were crosschecked to the existing theory and earlier publications in order to establish initial measurements. Throughout the demonstration phase of each publication, discrepancies to the control group were measured/identified with respect to the nature of technology in use, on an abstract level rather than unique brands or design solutions. Moreover, Publications B and C collect data from multiple experiments in laboratory and field settings where the measured discrepancies in each publication converged and were then theoretically supported in Publication D.

*Determining Boundaries – External Validity*

With consideration for the aim of this research, the efficiency of flexible fixtures was investigated within manufacturing industry. Therefore, the primary data source is identified as manufacturing industry. Having a broad context, this thesis employed the definition of a manufacturing system given in section 1.1, where manufacturing is treated as the zenith of a hierarchy with production systems exhibiting different characteristics. Within that definition, the data gathering activities are decoupled from the type of manufacturing industry (i.e. automotive or aerospace), the characteristics of which are emphasised in the findings. Based on that reasoning, the data richness with respect to manufacturing systems is evaluated within the range spanning from mass production to customisation. The range employed aims to show the requirements of types of manufacturing systems decoupled from the workpiece specific to individual systems. These characteristic differences are explained in detail in ElMaraghy [101] and Wiendahl, et al. [133]. Within this range, Publication A and D offer studies from the automotive industry where the characteristics of mass production are more dominant. Publications B and C, on the other hand, describe studies from the aerospace industry and occupy a position closer to customisation. The second perspective from which external validity is investigated is data richness in process requirements. In all publications, three processes provided fundamental fixturing inputs. These processes are *sealant application* in Publications B and C, *drilling* in Publication C, and *spot welding* in Publications C and D. Consequently, two possible threats have been identified as:

- In order to extend into the area of manufacturing industry, characteristics related to these higher levels of customisation need to be studied.
- Those processes that make more extreme demands on constructs may have an impact on the efficiency of fixtures.

The remaining perspectives are in correlation to the flexible fixture classification scheme presented in section 2.2.3. Thus, the third validation perspective describes the versatility of the physical form. In Publication A, a fixture mainly comprised of rebuilding features is analysed. The remaining publications utilise fixtures with reconfigurable form where standardised kinematic structures are subjects of experimentation. The fourth perspective represents the data richness in fixture actuation types. In Publications B and C, internally actuated fixtures are investigated. In Publication D, the experiments are conducted on an externally actuated fixture. In Publication A, manual actuation schemes are analysed. The fifth perspective is on the positioning/connection of flexible fixtures where all publications utilised only mechanical connections. The final perspective focuses on the data niche on fixture activeness. Publications B and C provide analysis and experiments on internally supported active fixturing whereas the remaining publications analyse fixtures utilising external intelligence tools. Consequently, the possible threats in the last four perspectives are identified from the viewpoint of the fixture's physical form and connection type. From a physical form perspective, there is a lack of data on phase-changing fixtures. However, due to the safety concerns specified in Chapter II, phase-changing materials are delimited from this research. Moreover, in order to include the possible effects of magnetic connection types, this thesis treated the efficiency criteria related to design and set-up operations by cost and time parameters. This means that for any shifts in the connection type from mechanical to magnetic form, the possible impact can also be treated by the same parameters. The illustration of the collected data with respect to the boundaries and delimitations of this thesis is illustrated in figure 23.

The final factor affecting external validity stems from the setting of the studies conducted. Each publication has been designed in either a laboratory or field setting; meaning that in an industrial setting, further characteristics might emerge. Moreover, the manufacturing system and process domains need to be extended – which eventually leads to the future work of this research as presented in the following section.

## 5.3 FUTURE WORK

The prospect of increased efficiency forms the basis of the future of this research. It is to this end that the exploration of efficiency has been conducted. However, in order to fulfil the aim of this research, three subjects need to be analysed. Firstly, the verification and validation of the understanding of efficiency will be tested in various manufacturing systems and processes to confirm or reject/improve the developed understanding. In parallel to DRM, this corresponds to the evaluation in *Descriptive Study I*. Second, by utilising the proposed design procedure and efficiency criteria, the development of a knowledgebase for fixture design will be in focus. This subject will establish the *Prescriptive Study* phase of DRM. Finally, providing experimental proof for the flexible fixtures with higher efficiency will be the centre of the research activities.

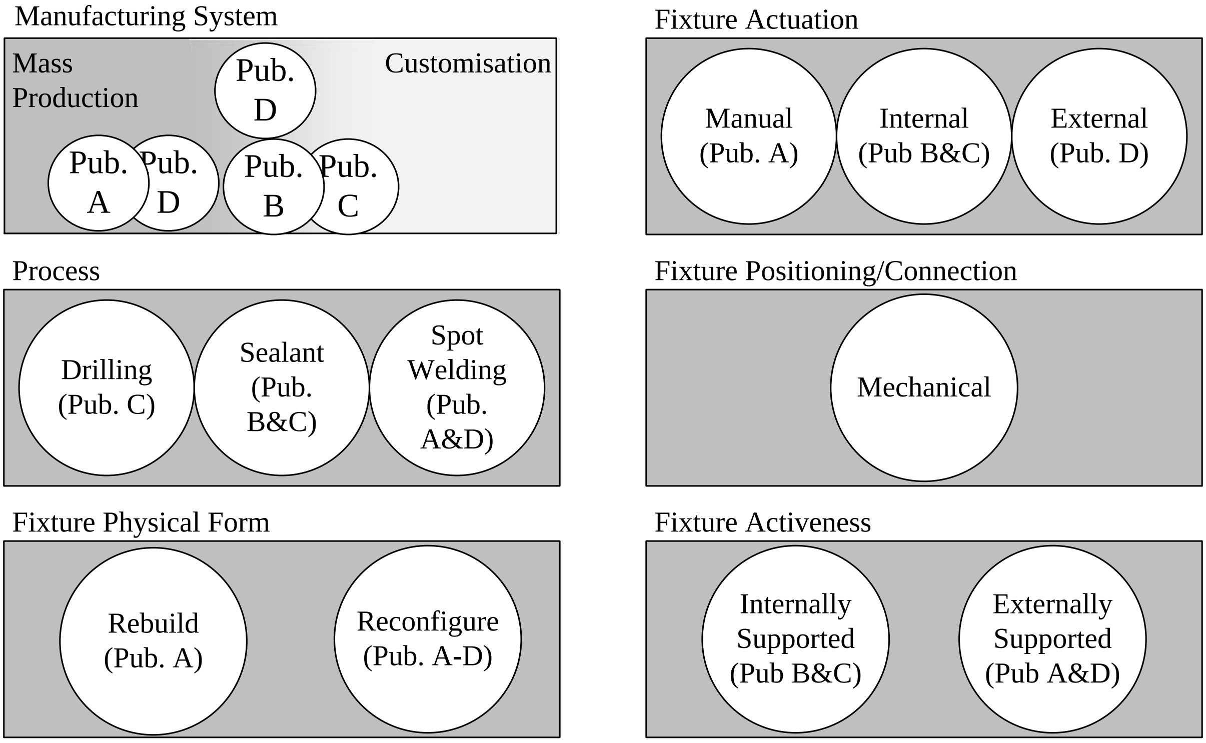



Figure 23. Sources of data with respect to the boundaries of this thesis and delimitations

# VI

# CONCLUSION

In concurrence with the stated objective of the research, this thesis developed an understanding of design and efficiency in flexible fixtures. The presented results were gathered by applying the existing theory of fixture design to aerospace and automotive industries. Continuously contributing to the body of knowledge, the territory of efficiency is charted by means of establishing criteria for efficiency. Moreover, the metrics and their use in a design procedure is presented. Subsequently, the relevant background encapsulated by criteria, metrics and a procedure is provided to increase the efficiency of flexible fixtures.

The efficiency of a flexible fixture can be described from three main perspectives: (i) technological capability, (ii) methodical design process, (iii) adaptation to the performance and characteristics of a prospective manufacturing system. Within these perspectives, the studies conducted identified seven criteria that can be used to describe and increase the efficiency of a flexible fixture. These criteria are related to:

1. *Physical capability of a fixture to satisfy circumscribed workpieces and processes*
2. *Contribution to the process quality*
3. *Interaction with other resources*
4. *Reconfiguration and/or rebuilding time*
5. *Modularisation by standardisation*
6. *Capital cost*
7. *Maintainability*

However, increasing the efficiency of a flexible fixture relies on the methodical use of these criteria. Through the implementation of fundamental features – standard kinematic structures with identified actuation and position holding types – a design procedure methodically using the criteria in the form of metrics can be realised. With a weight function that adapts the characteristics of a manufacturing system, the metrics are integrated into final efficiency. After computing the final efficiency value, the proposed design procedure offers two possible options to increase the efficiency by choosing between:

(I) flexible fixtures with different fundamental features to detect the fixturing solution with highest efficiency or

(II) the components in an individual flexible fixture to identify and replace the source of inefficiency.

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