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Integrated Assessment of Assembly fixtures Re-configurability

Diana Naser
University of Windsor

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By

Diana Naser

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By

Diana Naser

APPROVED BY:

____

A. Asfour
Departmental of Civil and Environmental Engineering

____

W. ElMaraghy
Department of Mechanical, Automotive and Materials Engineering

____

H. ElMaraghy, Advisor
Department of Mechanical, Automotive and Materials Engineering

Nov 28th, 2019

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ABSTRACT

The needs of consumers are changing over time. As a result, the manufacturers are looking for new methods to adapt effectively and efficiently to market changes. These involve supplying customers with a variety of products in a reasonable time with decreasing the cost. Reconfigurable fixtures are an important means for dealing with increased product variety and shorter life cycles, as they help change between the product variants effectively and decrease the time and resources required to introduce new product variants. In this thesis, an integrated method to assess the reconfigurability of assembly fixtures is developed. This assessment is based on four core reconfigurability characteristics: scalability, modularity, convertibility, and customized flexibility. A clear definition of the scalability of the reconfigurable assembly fixtures was developed. A mathematical model for each characteristic of reconfigurable assembly fixtures was developed. Their indices were determined then combined using a radar plot to assess the reconfigurability of the reconfigurable assembly fixture. Welding tack fixture is chosen as a case study in this thesis. Two redesign recommendations were proposed. The results showed the most appropriate design with highest reconfigurability index because it was designed to produce the same number of product variants with less reconfiguration time, cost, effort, and complexity. The significance of research in this thesis is to help in the design stage of the assembly fixture by comparing different configurations for the assembly fixture to choose the best one and suggesting some changes for the assembly fixture design and configuration. This is essential to minimize the number of fixtures to be produced when the new part component/ variant is introduced.

DEDICATION

To my father and siblings, for their encouragement, love, motivation, and support

To my supervisor, for her help, assistance, and guidance

To my mother, the most important person, who I miss a lot, for her love and encouragement when she was here, I always feel her soul is with me

ACKNOWLEDGEMENTS

I want to give a special thanks to Dr. Hoda ElMaraghy for her guidance and help throughout this research. Her consistent support was truly inspiring, and the reason for the development and completion of this thesis. I want to pass the highest appreciation to the committee members, Dr. Waguih ElMaraghy and Dr. Abdul-Fattah Asfour, for their valued comments and suggestions, especially during the proposal. Also, I would like to thank the industrial Engineering and manufacturing systems faculty members and staff for all the support they provided throughout. Lastly, I would like to express my great, utmost appreciation to my family and friends, for their endless support and patience with me has greatly motivated me.

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LIST OF ABBREVIATIONS/SYMBOLS

RAF	Reconfigurable Assembly Fixture
RMSs	Reconfigurable Manufacturing Systems
DMSs	Dedicated Manufacturing Systems
FMSs	Flexible Manufacturing Systems
CMSs	Changeable Manufacturing Systems
MCDM	Multi-Criteria Decision Making

NOMENCLATURE

M	The modularity of the reconfigurable assembly fixture.
N_{st}	The number of standard modules in the reconfigurable assembly fixture that will not be removed or replaced during the conversion
N_T	The number of total modules in the reconfigurable assembly fixture.
C	The convertibility of the reconfigurable assembly fixture.
N_p	The number of product components.
C_f	The customization flexibility of the reconfigurable assembly fixture.
N_f	The number of fixtures that are replaced (the number of fixtures that previously required to do the same task).
T_{rec}	The reconfiguration time for the reconfigurable assembly fixture.
T_T	The reconfiguration time (changeover time) of the entire fixture.
S	The scalability of the reconfigurable assembly fixture.
$N_{a/r}$	The number of modules added, removed, or replaced.
N_a	The number of modules that need to be added.
N_r	The number of modules that need to be removed.
N_{rp}	The number of modules that need to be replaced.
N_m	The number of modules that need to be moved during the conversion.
S_s	A similarity coefficient between different configurations of a reconfigurable assembly fixture.
N_s	The number of modules that will not be adjusted during the conversion.

a The shaded radar plot area.

A The total radar plot area.

C_i The normalized code value on the radial axis of digit i for each radar plot.

R The reconfigurability index for each class.

CHAPTER 1

INTRODUCTION

1.1 Research Motivation

In recent years, trends in customer needs and requirements have changed significantly, and the world economy is now complicated and unpredictable. The manufacturing sector is greatly influenced by the buyer market, from fluctuations in product demand to product diversity. The trend has become of customized production. Consequently, it is important to offer product variety to meet market changes and different customer requirements. Designing that variety of products needs to design different kinds of fixtures. In general, designing a new fixture should first consider some essential aspects, as shown in figure 1.1.

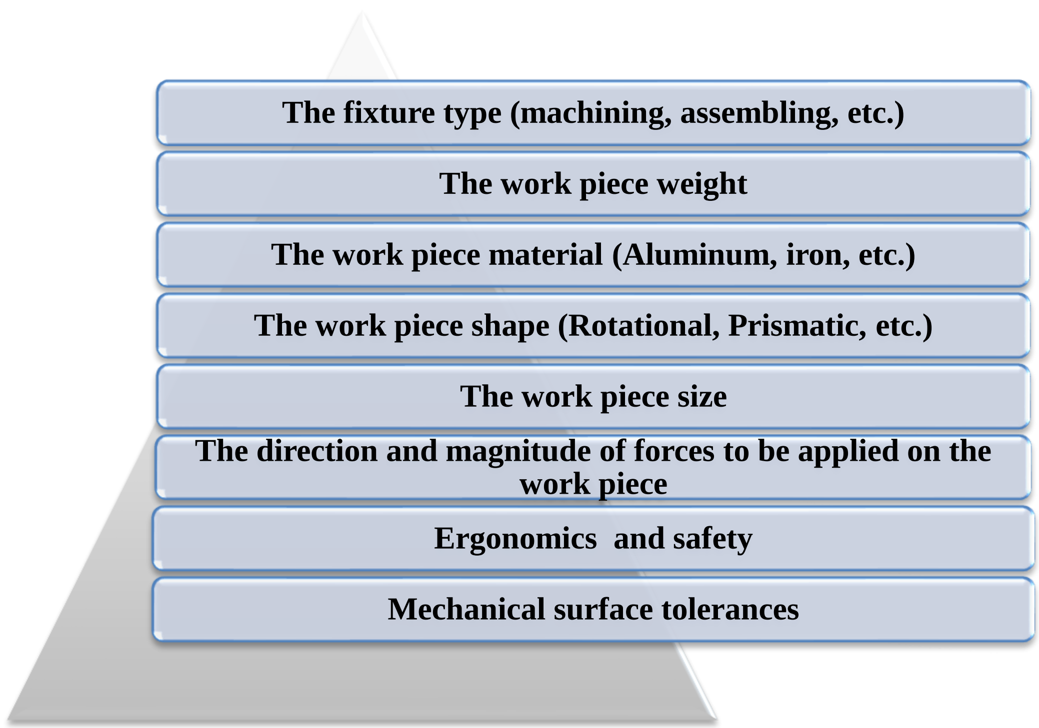


Figure 1.1: Important factors to design a new fixture

In industry, assembly operations are traditionally performed with the aid of large and permanent fixtures, which are costly to design and manufacture, especially for the large size and heavyweight work pieces (Sequeira & Basson, 2009). The set of requirements for fixtures began to develop with new manufacturing paradigms. An example of this can be seen with the introduction of Reconfigurable Manufacturing Systems (RMS). The RMS effect has shaped the nature of the fixture from dedicated to modular and reconfigurable, with many research works to find optimum fixturing solutions. The fixture reconfiguration is essential due to its ease of modification and re-use of fixtures for reducing cost and fixture change process time.

Many design approaches for reconfigurable assembly fixtures have been presented, but the assessment of the reconfiguration of those fixtures has not been sufficiently addressed yet. Very few researchers mentioned some of the characteristics of the reconfigurable assembly fixtures, but they did not define and combine them in a single framework.

In this research, the assessment of the reconfigurable assembly fixtures is presented based on four core characteristics (Scalability, Modularity, Convertibility, and customized flexibility), which are defined and measured. The quantitative indices for the four features are combined using the radar chart method to measure the reconfigurability of the fixture and develop an overall index for it.

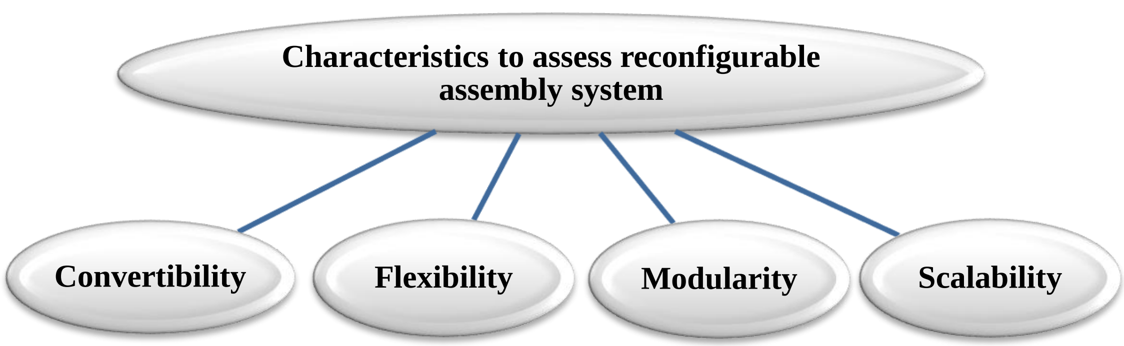


Figure 1.2: Characteristics to assess the configuration design of the reconfigurable assembly fixture

1.2 Statement of Engineering Problem

The main reason for designing too many different dedicated assembly fixtures is to cope with different kinds of parts, product variants, or different processes. Due to the rapid change in manufacturing and the customer requirements, the need to design reconfigurable fixtures with less reconfiguration time and cost is very significant. The designers of new configurations of fixture are able to offer a variety of feasible reconfiguration schemes, but an integrated framework and model to choose the most appropriate one is needed. Moreover, the complexity of reconfigurable assembly fixtures increases because of the increasing the number of modules in the fixture. The need to assess the reconfigurability of the fixture considering the complexity, reconfiguration time, and the number of products and processes that the fixture can be used for is to make some recommendations about the designing of the fixture.

1.3 Objective

The main objective for this thesis is to develop an index to assess reconfigurable assembly fixture by providing a set of composite reconfiguration measures which define indicators of the principal reconfigurable assembly fixtures features to measure its reconfigurability. This would help in the initial design phase to choose the most appropriate design for the fixture considering the time, the number of product variants that the fixture can handle, and the number of modules in the fixture.

1.4 Contributions

The contributions of this thesis help in the design stage of the assembly fixture by comparing different configurations of the assembly fixture to select the most appropriate one to meet the anticipated product variations. Moreover, making some recommendations for the assembly fixture design and configuration is essential to minimize the number of fixtures to be produced when a new part/product component/ variant is introduced.

These contributions are:

- Introducing an integrated method to assess the reconfigurability of assembly fixtures. The assessment is based on four core reconfigurability characteristics: scalability, modularity, convertibility, and customized flexibility.
- Developing a clear definition of the scalability of the reconfigurable assembly fixtures.
- The developed measurements of the scalability, flexibility, and convertibility based on different parameters were not covered in the literature.
- Measuring the characteristic of reconfigurable assembly fixtures (scalability, flexibility, and convertibility) includes providing quantitative data matrix evaluation indices by analyzing the meaning and significance of each index and the parameters related to that index.
- The combination of quantitative indices of the four characteristics in an integrated mathematical model and using the radar method to combine them into a reconfigurability index for a reconfigurable assembly fixture is new and was not introduced before.

1.5 Scope of Research

The scope of this research and the boundary of the work are outlined as follow:

- The type of fixtures is reconfigurable, adaptable assembly fixtures.
- Manufacturing system types: flexible and reconfigurable manufacturing system.
- Product variety: product families.
- Production: medium volume and medium variety.
- Size of fixtures-is: large.

1.6 Research Hypothesis

Measuring the characteristic of reconfigurable assembly fixtures includes providing quantitative data matrix evaluation indices by analyzing the meaning and significance of each index and the parameters related to that index.

Each feature in reconfigurable assembly fixture would have a dimensionless index that falls within the range of 0–1, with a near-1 index indicating a higher index of this characteristic and a near-0 index indicating a lower index.

Developing a tool to measure the reconfigurability of the fixture based on the reconfigurability characteristics will help the designer to design fixtures that could accommodate different products with less reconfiguration time/effort.

1.7 Thesis Structure

This thesis is set up into five chapters:

- Chapter 1 discusses the motivation, problem statement, and research objectives.
- Chapter 2 contains the literature review and knowledge concerning this thesis' topic.
- Chapter 3 explains the developed methodology mathematical model for assessing the reconfigurability of assembly fixtures.
- Chapter 4 includes research results, case studies, and discussions.
- Chapter 5 presents conclusions and recommendations.

CHAPTER 2
LITERATURE REVIEW

2.1 Overview

In this chapter of the thesis, a large amount of previous work addressing different types and designs of fixtures are reviewed. The first section of the literature survey is concerned with the topic of reconfigurable assembly systems. It includes the definition of the reconfigurable manufacturing system and its assessment based on its characteristics, including those that could be considered for the reconfigurable fixtures. The second section of the literature survey is about reconfigurable assembly fixtures. Also, different design approaches are presented. It includes a detailed review of categories of the reconfigurable fixtures and their definitions. The third and last section of this chapter is about the assessment of reconfigurable assembly fixtures and the different assessment strategies used for different types of reconfigurable assembly fixtures.

2.2 Reconfigurable Assembly Systems

Manufacturing systems or manufacturing are the steps or processes that the raw materials go through to transform into a final product. An assembly system is the most critical level in the manufacturing system where the components of the product or subassemblies of products are joined together to create a final product. There are different types of manufacturing systems. Each system has its advantages and disadvantages so, choosing appropriate the manufacturing system type is important to maintain the high quality of the final product, more efficient production processes, high production volume, and less cost.

The manufacturing systems have developed over the years and evolved from traditional to conventional to advanced systems. In the past, the production was stable, and the number of variants did not satisfy customer demand. Also, the production was taking too much time to produce a limited number of products. Due to the rapid change in customer demand and the need to satisfy the customer and environment requirements such as more variants, low cost, and short lead time, the industries today are moving to use more flexible and responsive manufacturing systems (Bi, Lang, Shen, & Wang, 2008). The three categories of manufacturing systems that are classified by ElMaraghy are dedicated machining systems (DMSs), flexible manufacturing systems (FMSs), and reconfigurable manufacturing systems (RMSs). Each category has significant benefits. The production of the dedicated manufacturing system is fixed over a lifetime. On the other hand, a flexible manufacturing system is designed to produce a variety of products belonging to a family of variables produced in changeable production volumes. Also, reconfigurable manufacturing systems are designed to meet a specific range of production requirements (ElMaraghy, 2005).

There are many characteristics of changeable manufacturing systems (CMS) at the physical (hard) and logical (soft) levels (ElMaraghy, 2005). Reconfigurable manufacturing (such as machining or assembly) refers to the physical aspects of change on the shop floor affecting machines or parts of robots, fixtures, and layout and is enable by reconfiguration ability, among other factors (Jonsson et al., 2010). RMS includes six characteristics that control the system's ability to change physically. These characteristics are modularity, customized flexibility, integrality, scalability, diagnosability, and convertibility (Koren et al., 1999). Rapid changes in customer demand also increase the importance of the need for a reconfigurable manufacturing system and improve their main feature, which is the responsiveness. The responsiveness is the ability of the production system to respond to changes in external demand and internal conditions and events on the shop floor.

The reconfigurable manufacturing system concept and strategy has changed the nature of the used fixture from just modular to reconfigurable, with many different researchers who are trying to find optimal fixturing solutions to enhance the reconfigurable manufacturing systems ability to adapt to changes in the shape, size, and functions in the produced part/product family (Jonsson et al., 2010). It should be noted that fixtures only adapt to changes in the product, not the production volume. Only if production volume is very high does it become more economical to use a dedicated fixed manufacturing systems and fixtures which are optimized for large production runs.

2.2.1 The assessment of reconfigurable assembly system characteristics

Due to the importance of the reconfigurability of the manufacturing system, many different studies have covered the assessment of reconfigurable manufacturing systems. These studies covered two aspects; the first aspect is providing a set of composite metrics translating indices for the characteristics of the reconfigurable manufacturing system, and the second aspect is providing the global reconfigurability indices to assess the reconfigurability of the reconfigurable manufacturing system. Many different studies covered the second aspect ((Goyal et al., 2012), (Goyal et al., 2013), (Hasan et al., 2013), (Hasan et al., 2014), (Benderbal et al., 2015)).

Moreover, most of these studies used multi-criteria decision making techniques for evaluation to help choose the most appropriate approach ((Gumasta, Kumar Gupta, Benyoucef, & Tiwari, 2011), (Wang et al., 2017), (Goyal et al., 2012), (Goyal et al., 2013), (Hasan et al., 2013), (Farid, 2017), (Garbie, 2014), (Hasan et al., 2014), (Michalos et al., 2015), (Mourtzis et al., 2012), (Michalos et al., 2011)). The multi-criteria decision making steps start by the criteria selection and weighting, evaluation, and then the final assessment (Wang et al., 2009).

Gumasta et al. (2011) used a multi-attribute utility theory to develop an index to combine the measures of the reconfigurability for four characteristics (modularity, scalability, convertibility, and diagnosability) of the reconfigurable manufacturing system. The reconfigurability index in this method depends on the relative importance of different characteristics. Wang et al. used different way method to assess reconfigurable manufacturing systems (Wang et al., 2017). This method includes two-stage of evaluation (AHP and PROMETHEE), which are efficient due to the most precise index of the reconfigurability of the system that reflects six attributes of the system. PROMETHEE is very beneficial to assess reconfigurable manufacturing systems because it measures reconfigurability in two steps (Wang et al., 2017). The first step; shows the advantages and disadvantages of each configuration of the system. The second step ranks the advantages result from the best to the worst. The first step called PROMETHEE I which applied to indicate the advantages and disadvantages of each alternative scheme. PROMETHEE II is the second step which is adopted to analyze the net advantages of the schemes. Farid offered the combination of integrability, convertibility, and customization measures that have driven the qualitative and intuitive design of these technological developments (Farid, 2017). All these methods and more were used to assess the reconfigurability of manufacturing systems.

2.3 Introduction to Fixtures and Fixtures' Types:

A fixture is defined as a device that holds the work piece while applying manufacturing operations such as machining, assembly, and inspection. The primary functions of the fixture concerning the work piece are locating, clamping, and supporting (Li et al., 2006).

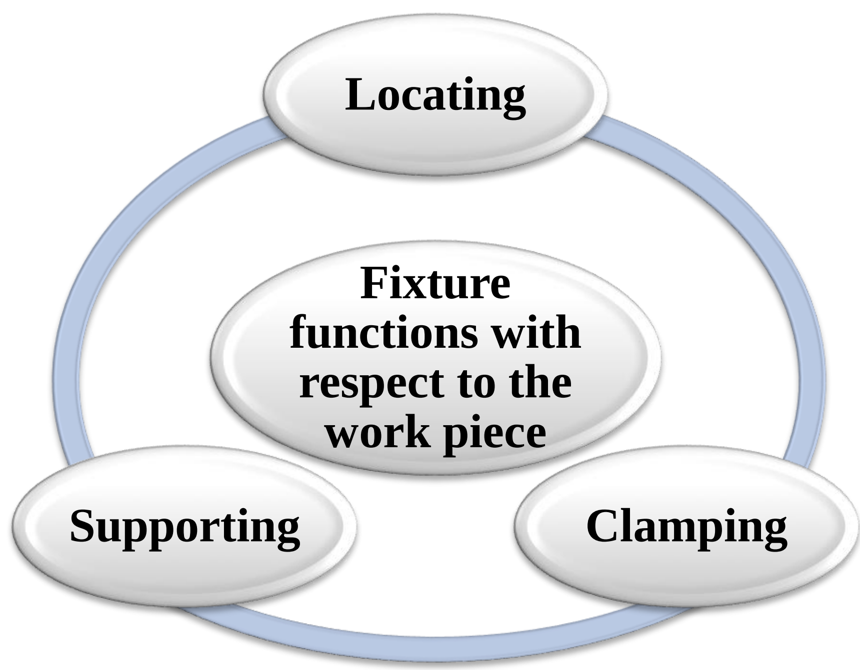


Figure 2.1: The primary function of the fixture concerning the work piece presented by (Li et al., 2006)

Li et al. (2006) classified the fixture based on the functionality concerning the work piece includes:

a. Locating: positioning and orienting a work piece accurately.
b. Clamping: stiffening the work piece in its intended position precisely.
c. Supporting: increasing the rigidity of a work piece of part compliant areas.

The importance to make these functions: supporting, locating and clamping more adjustable is to accommodate the different shapes and sizes of the parts in a part family.

Li et al. (2006) classified two-part families; the first one has the same shape and the second one has the same size. He developed reconfigurable fixturing system for them counting vertical support, horizontal support, vertical clamp, horizontal clamp, and a reconfigurable index table.

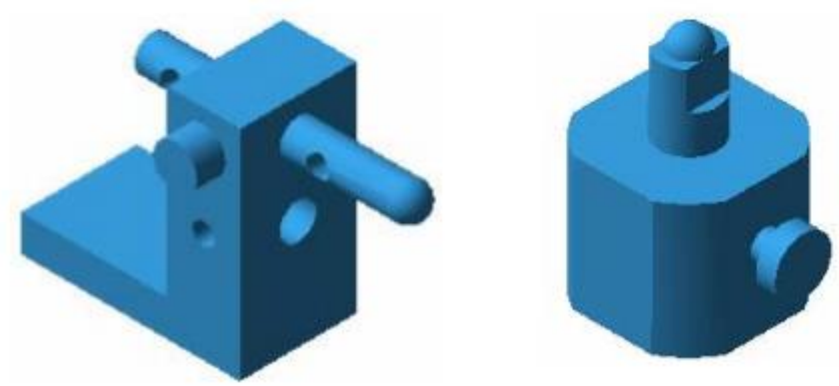


Figure 2.2: Reconfigurable vertical locator and reconfigurable horizontal locator presented by Li et al. (2006)

This research does not focus on the functionality of the fixture, but it focuses on the design of the fixture.

Erdem (2017) classified the fixtures into three groups of fixtures based on the design of the fixture. The first category, "rebuilding fixtures," representing fixtures that require the complete or partial structure to be rearranged in order to allow flexibility. The second category is a phase-changing fixture. This class reflects all fixtures that use phase-changing technology to protect a work piece. The third category is reconfiguring fixtures; it outlines fixtures that allow flexibility by changing certain parameters internally. This research focuses on the third class which is reconfiguring fixture.

Li et al. (2005) followed machine tools to categorize the types of the fixture as dedicated, reconfigurable, or flexible.

The designing of the fixture depends on the work piece, applied forces during processing, and the materials of the fixture to be sufficiently strong and withstand the applied loads (process or due to weight), etc. In general, designing new fixture should first consider some critical aspects. These factors to design a new fixture are the fixture type (machining or assembling), the work piece weight, the work piece material and strength (Aluminum, iron, etc.), the work piece shape (Rotational, Prismatic, etc.), the work piece size, the direction and magnitude of forces to be applied on the work piece, ergonomics and safety and mechanical surface tolerances. These aspects should be first listed to consider the shape and the features of the fixture.

Dedicated fixtures are designed to hold only a specific part for specific manufacturing operations. This type of fixture can involve frequent and time-consuming changes when the variety of products is high relative to the volume of production. Each time a new part or product is introduced, a new fixture needs to be developed that add to the total number of fixtures to be stored and handled throughout the product life. The design and manufacture of fixtures may cost up to 10–20 percent of the total price of an FMS in isolation (Bi et al., 2008).

On the other hand, the flexible fixtures are defined as a fixture that could be used for general purposes with different product/parts structures. Li et al. (2006) summarized that and compared those three types of fixtures in one table. Table 2.1 shows the similarity and differences among them.

Table 2.1: The differences and similarities between three different types of fixtures

Fixture	Dedicated	Reconfigurable	Flexible
Design Focus	A particular part	A part family	General purpose
Structure	Fixed	Adjustable	Case – dependent*
Flexibility	No	Customized	General
Production	Mass	Batch – Mass	Job – Batch
Convertibility time	Not convertible	Fast	Slow

*The structure of the modular fixture is changeable, but it is fixed for the multi-pin fixture type.

The modular fixture systems are a well-known and widely used concept when it comes to the development of CNC machines.

Moreover, some fixtures have adaptive property, and they are called "Adaptable fixtures," which means they adapt or adjust to the geometry of the work piece. The adaptability of the fixtures depends on the holding force contact points and areas (Youcef-Toumi and Buitrago, 1989).

There are six categories of the adaptable surface fixturing systems. These are fluidized bed vise, multi-leaf vise, programmable conformable clamps, encapsulation, exchangeable Jaw Vise, and reconfigurable modular fixtures.

The importance of adaptability is that the fixture does not allow any displacement or rotations in the degree of freedom that the work piece or part can move. This property could be exhibited in the types of fixtures: flexible fixtures, dedicated fixtures, and reconfigurable fixtures.

In this thesis, the adaptability property is considered due to its importance for preventing the displacement or rotation of the work pieces in the reconfigurable fixtures.

The reconfigurable fixture is more focused on the part family. This type of fixture requires less time conversion/reconfiguration time than the flexible fixtures. In general, the idea of the reconfigurability of the fixtures comes from the reconfigurability of the system.

2.3.1 Reconfigurable assembly fixtures

The reconfigurability is not just essential for the manufacturing system, but it is also essential for the fixtures. Reconfigurable fixtures are a vital way of confronting the increasing variety of products and shorter lifecycles as they help to more efficiently change product variants and reducing time and resource use for new product versions. The reconfigurability of fixtures could be defined as the adjustment activity of a fixture using built-in features such as reconfiguring the leg length of a linear actuator. A reconfigurable fixture can be reconfigured rapidly in comparison to the flexible fixtures (modular fixtures) since only part variants within a family are changed. Thus, a reconfigurable fixture utilizes both standard modules that can be reused and unique modules designed for a particular part or product part that allows a quick change between various layout configurations, to accommodate variants in a part or product family (Jonsson and Ossbahr, 2010).

Many types of research have been reported about reconfigurable fixtures. Bi et al. (2008) indicated that there are two types of reconfigurable fixtures; modular fixtures and integral flexible fixtures. For the modular fixture, which is the focus in this thesis, Chan and Lin (Chan and Lin, 1996) reported on developing flexible modular grippers that match an arbitrary working surface using several multi-fingers. As shown in figure 2.2.

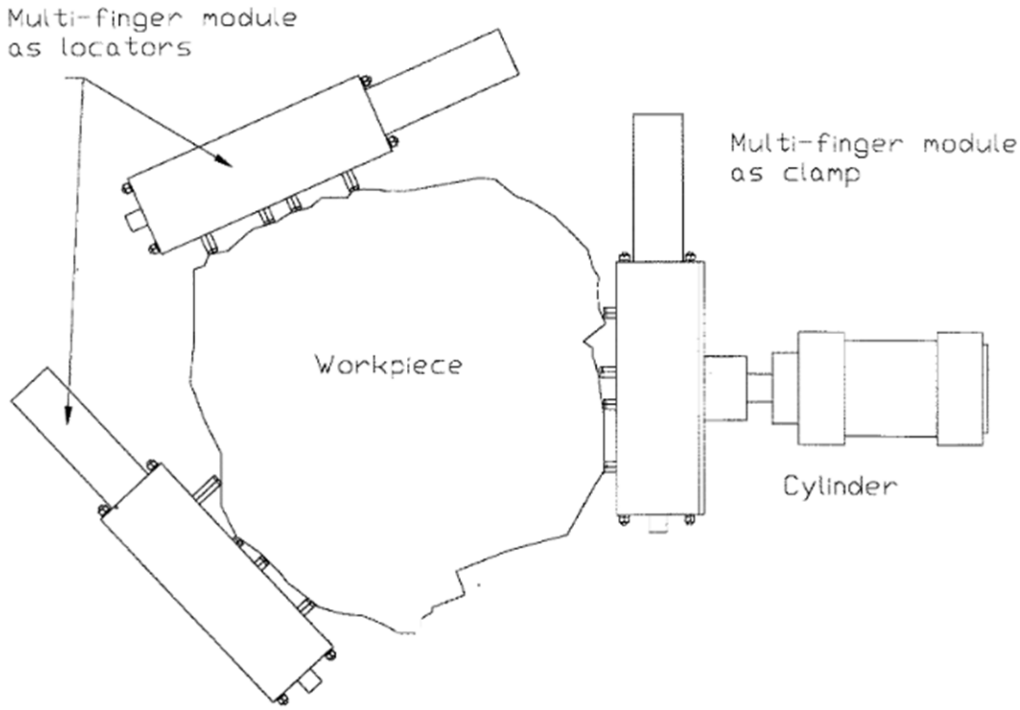


Figure 2.3: CNC modular fixture for assembly presented by Chan and Lin (1996)

Sela et al. (1997) developed a modular fixturing system in order to fasten thin-walled objects with a discrete number of dedicated point forces. Bejlegaard et al. (2018) developed a methodology for designing generic architecture for reconfigurable fixtures. For the design of reconfigurable fixtures, a developed method for reconfigurable production systems design was adapted. The method is validated by applying it to an industrial welding task, allowing 14 different subcomponents to be assembled by using one single reconfigurable fixture, for which six different fixtures were previously necessary.

Moreover, Siong et al. (1992) traced the evolution of modular fixture systems and their impact on high - precision machining industries. The strength of the current computer-aided tools for modular fixture design is examined along with their weaknesses. Erdem (2017) established his thesis about the design and the efficiency of flexible fixtures. The comparison of the design methodology of the three designs was presented in his thesis. Olayinka et al. (2015) established a paper about a detailed design analysis of parts of the reconfigurable assembly fixture of the press brake frame. Papastathis et al. (2010)

developed a reconfigurable fixture for the automated assembly and disassembly of high-pressure rotors for Rolls-Royce Aero engines.

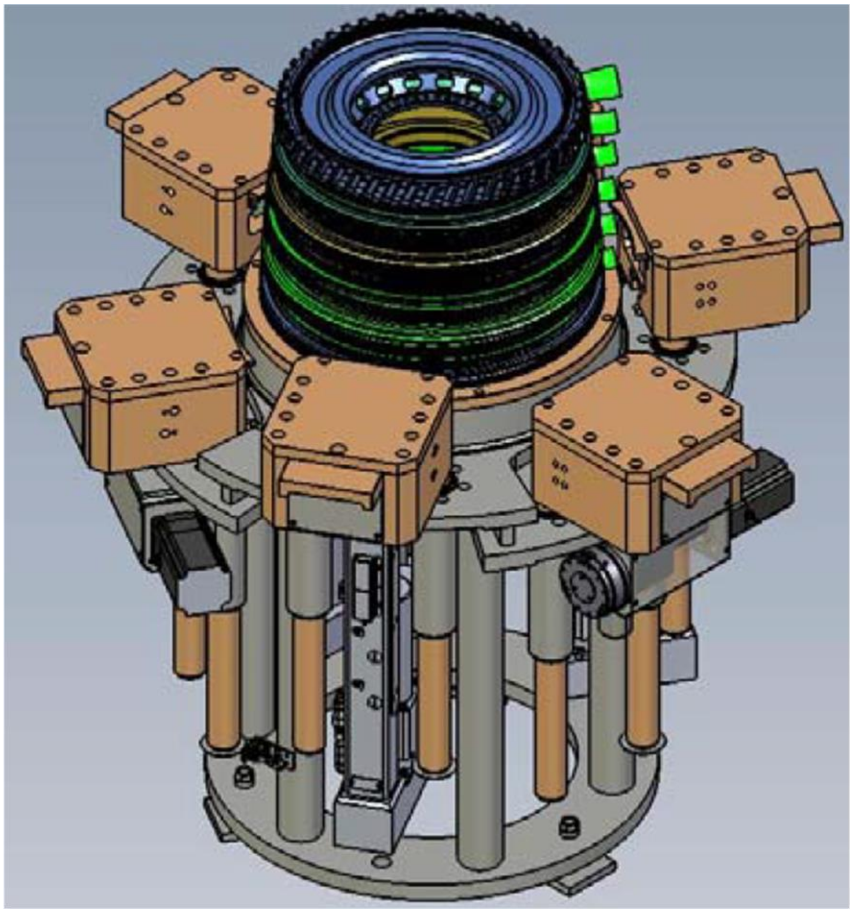


Figure 2.4: Simplified design overview of the fixturing system presented by Papastathis et al. (2010)

Jonsson developed different methods used to position and reconfigure flexible fixtures using a parallel kinematic device (Jonsson and Ossbahr, 2010).

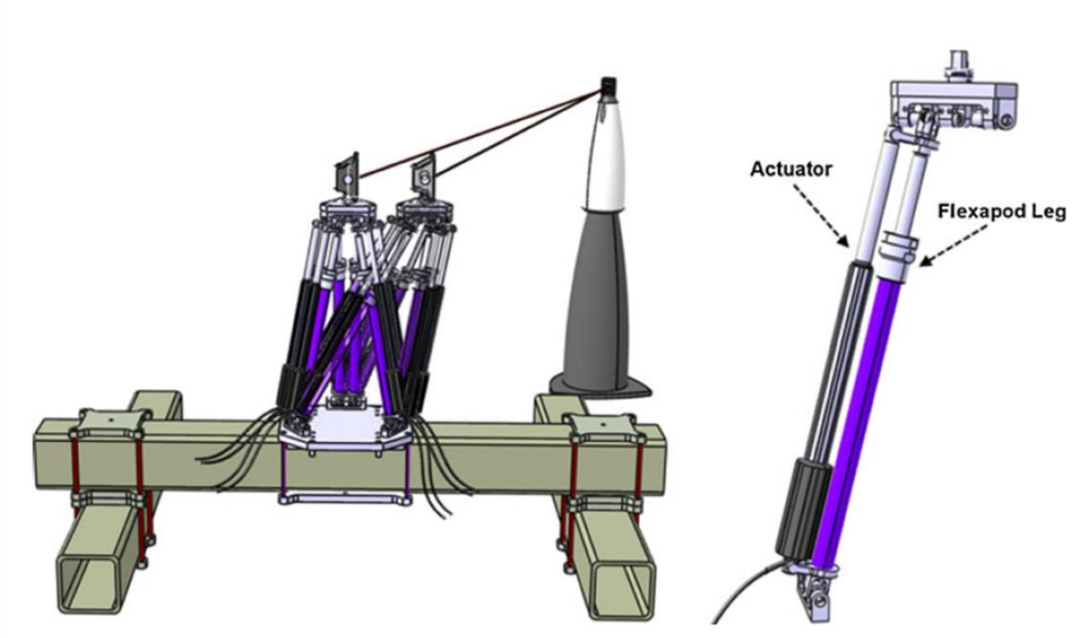


Figure 2.5: Flexapod with motor-driven actuator attached to the legs. An outer measuring system ensures accuracy presented by Jonsson et al. (2010)

On the other hand, the second type of reconfigurable fixtures is the integral fixtures, which includes the robotic grippers and face-change flexible fixtures. Bi et al. (2008) presented different robotic grippers, usually with simultaneous finger work. Moreover, he indicated that the flexible phase-change fixturing is based on the idea of phase-change in the material and can be induced either by temperature, electricity, or combination. Fan et al. (2018) developed a reconfigurable fixture for aero pipeline assembly before welding which includes three systems; mechanical system, configuration system and control system. This fixture system can enhance the assembly and effectiveness of a wide range of pipelines substantially. Helgosson et al. (2010) developed the configurable and modular steel construction fixture system, as shown in figure 2.5. Many other examples of different methodologies for reconfigurable structural fixtures are developed for assembly purposes ((Millar and Kihlman, 2009), (Shen et al., 2006), (Jefferson et al., 2016), (ElMaraghy and AlGeddawy, 2015), (Li et al., 2018), (Xia et al., 2017)).

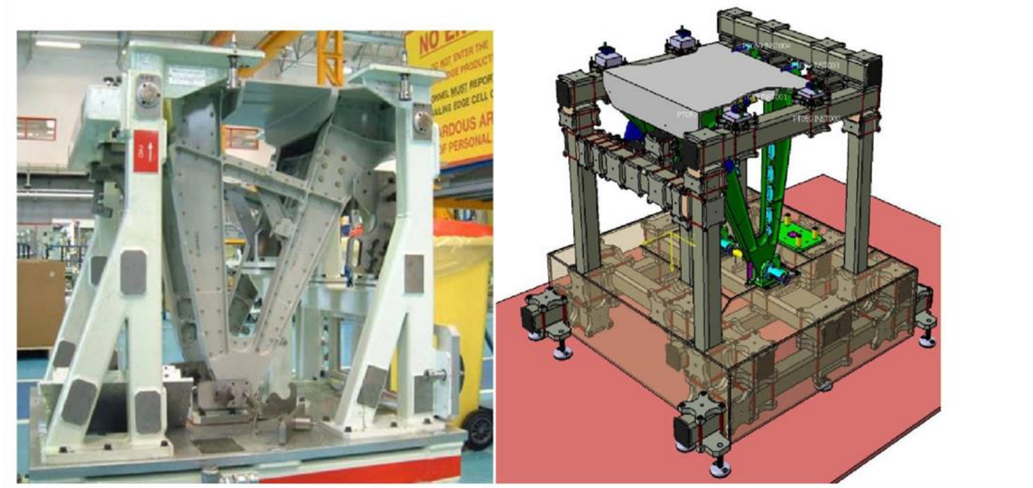


Figure 2.6: a. Existing Conventional A380 Rib 17 Subassembly fixture (courtesy of Airbus UK) b. The modular and configurable version of the A380 Sub-assembly fixture by Helgosson et al. (2010)

The majority of reconfigurable fixtures listed above are prototypes, and there has not been a common approach or design method.

2.3.2 The assessment of the characteristics of reconfigurable assembly fixtures

Reconfigurable assembly fixture is essential to make that change to the manufacturing paradigm. Due to the rapid change in the domain, and the effective cost, the need for the reconfigurable assembly fixture becomes more significant. In recent years, reconfigurable assembly fixtures have been developed for many different sectors. As a result of that, the need for assessment for the reconfiguration for assembly fixtures is essential to choose the appropriate design for the fixture that copes with different product variants. Bejlegaard et al. (2018) developed a methodology for reconfigurable fixture architecture design of two different features (usability and convertibility) of the reconfigurable assembly fixture and how it will financially affect the reconfigurable manufacturing system potential. Tohidi and AlGeddawy (2019) evaluated the performance and efficiency of the modular fixtures.

Also, different sizes of three different numerical examples are used. Bem et al. (2017) established a paper about reconfigurable fixture evaluation for use in automotive light assembly. The assessment was based on the stiffness of the locking mechanism and position accuracy while repositioning it, and the assessment was to determine whether the reconfigurable fixture can be reliably used in robotic assembly cells. Erdem (2017) compared the design procedure for reconfigurable assembly fixtures. In this paper, the definitions of the design parameters of reconfigurable assembly fixtures are presented and measured. The main parameters which were indicated are Modularity, which is defined as the ability to modularly rearrange a fixture for various applications, and flexibility, which is defined as the ability of the fixture to adapt to various products and processes.

The definitions of scalability and convertibility could be translated from the reconfigurable assembly system to reconfigurable assembly fixture since a fixture is a product, and a system depending on its complexity.

Table 2.2: Summary of the definition of each characteristic of the reconfigurable assembly fixtures.

<table>
<tr><td>Reconfigurable assembly fixture characteristic</td><td colspan="2">Definition</td></tr>
<tr><td>Modularity</td><td colspan="2">The ability of the assembly fixture to rearrange the modules for various applications (Erdem et al., 2017).</td></tr>
<tr><td>Flexibility</td><td colspan="2">The ability of the fixture to adapt to various products and processes within parts family (Erdem, 2017).</td></tr>
<tr><td></td><td>System</td><td>Fixture</td></tr>
<tr><td>Convertibility</td><td>The capability of a reconfigurable assembly system to rapidly adjust the assembly functionality, which includes the conversion of the hardware and software functionality within a family to meet the variations (Wang, 2017).</td><td>The ability of reconfigurable assembly fixture to quickly transform the functionality of existing modules and controls to suit new production requirements, which includes the conversion of the functionality of modules within a family to meet the variations.</td></tr>
<tr><td>Scalability</td><td>The ability of the reconfigurable assembly system to be modified to produce different variants of the part family by adding, removing, or replacing some modules (Wang, 2017).</td><td>The ability of the reconfigurable assembly fixture to be modified to produce different variants of the part family by adding, removing, or replacing some modules.</td></tr>
</table>

An integrated evaluation index is needed to assess the performance of the reconfigurable assembly fixtures. This index should be based on the key characteristics of the reconfigurable assembly fixtures.

2.4 Research Overview

Table 2.3: Research overview

Research methodology	References	Advantages	Deficiency
The assessment covers the characteristics of the reconfigurable assembly fixtures	Bejlegaard et al. (2018)	Show the importance of the reconfigurability and assess the potential cost and the convertibility.	No measurement for scalability, flexibility, and modularity of the fixtures.
	Tohidi & AlGeddawy (2018)	Assess the modularity of the fixtures.	The assessment focuses on just on the modularity of the fixtures and does not include other characteristics.
	Erdem et al. (2017)	Show the comparison between different configurations based on the flexibility and the modularity of the fixtures.	The assessment for the characteristics did not indicate the scalability of the fixture or give an efficient measure for its convertibility.
	Gumasta, K., Gupta, S. K., Benyoucef, L., & Tiwari, M. (2011).	Develop an index to combine the measures of the reconfigurability of characteristics.	The evaluation is for reconfigurable manufacturing system, not fixtures.
	Wang et al. (2016)	The assessment reflects the characteristic of the system.	The assessment is for reconfigurable

			manufacturing system, not fixtures.
Indicate the importance of reconfiguration in configuration evaluation	Goyal et al. (2012)	Indicate the importance of reconfigurability in configuration evaluation.	Used Two inefficient steps of evaluation, and it is for the system not for the fixtures.
	Erdem (2017)	Show the importance of reconfigurability and compare between different configurations.	The index of convertibility measurement is a binary number that will not give accurate results.

2.5 Research Gaps

Based on the conducted literature review in this chapter, the following research gaps were identified:

Table 2.4: Research gaps

	Li, Pasek & Adams	Papastathis et al. (2011)	Bem et al. (2017)	Jonsson & Ossbahr (2010)	Olayinka et al. (2015)	Erdem (2017)	Tohidi & AlGeddawy (2018)	Bejlegaard et al. (2018)
Measure fixture Modularity						✓	✓	
Measure fixture convertibility						✓		✓
Measure fixture Scalability								
Measure fixture Flexibility						✓		
Indicate the importance of the ability to reconfigure	✓	✓	✓	✓	✓	✓	✓	✓
Detail analysis of alternatives		✓						
Develop an evaluation index								

• The reconfiguration time for the reconfigurable assembly fixtures for measuring the characteristic of the reconfigurable assembly fixtures and the definition for the reconfigurable assembly fixture scalability were not covered.

• The measurement for the convertibility was not precise because it was a binary index, either 0 or 1 (Erdem, 2017).

• There is no research method to combine all the indices related to the reconfigurable assembly fixtures and developed evaluation index to assess the reconfigurability of assembly fixtures based on four core characteristics, i.e., scalability, convertibility, modularity, and customization flexibility).

2.6 Conclusion

The manufacturing environment for fixtures is changing to use more reconfigurable fixtures. The significance and benefits of developing an appropriate design for the fixture are obvious. Having said that, assessment of the reconfigurability of the assembly fixtures is required.

In this chapter, a review of the reconfigurable fixtures' definition and designs, especially for assembly, were presented. Since a fixture is both a product and a system with varying degrees of complexity, the definitions of scalability and convertibility can be adapted from the reconfigurable assembly systems to reconfigurable assembly fixtures. From the review of different definitions and measures of the characteristics of the reconfigurable assembly fixtures and reconfigurable assembly system, we observed that the most widely used metric is depending on the definition of each characteristic and translate that into equations to measure the index of each one. In addition, the need for an overall index to combine all these indices is essential to measure the overall reconfigurability of the fixture. Therefore, it would be beneficial to find the most appropriate design of the reconfigurable fixture.

Developing such a model will help manufacturers to design reconfigurable assembly fixtures with the least time and difficulty, and also fixtures could adapt to different processes and used for more variants. Also, this model will help to rationalize the various fixtures design alternatives. Choosing the most appropriate design will help in reducing assembly time and improving productivity.

CHAPTER 3

ASSESSMENT OF RECONFIGURABLE ASSEMBLY FIXTURES

3.1 Introduction

Manufactures adopt different methods to design different types of reconfigurable assembly fixtures. It is crucial for firms to effectively choose the most appropriate fixture for the manufacturing system to reduce the time and cost of the reconfiguration as well as overall time and cost. Numerous studies have attempted to develop different reconfigurable assembly fixtures but have not covered the method to assess the reconfigurability of those fixtures based on their characteristics; scalability, convertibility, modularity, and flexibility. Moreover, the way to choose the most appropriate fixture for the system has not been covered yet.

3.2 Methodology and Model Development

It is important to identify and analyze the problem and the details in order to find the right solution to the problem, which needs a tool that sorts the findings of an investigation into a structural framework. In this thesis, IDEF0 is used to model the actions and activities to assess the reconfigurability of the assembly fixtures.

In this section, this methodology to assess the reconfigurable assembly fixtures is presented, outlining the main parameters to undergo each of the main characteristics of the assessment. The IDEF0 function includes four main parameters. These parameters are input, output, mechanisms, and constraints.

Figure 3.1 shows the IDEF0 for the process model proposed in this research.

3.2.1 IDEF0

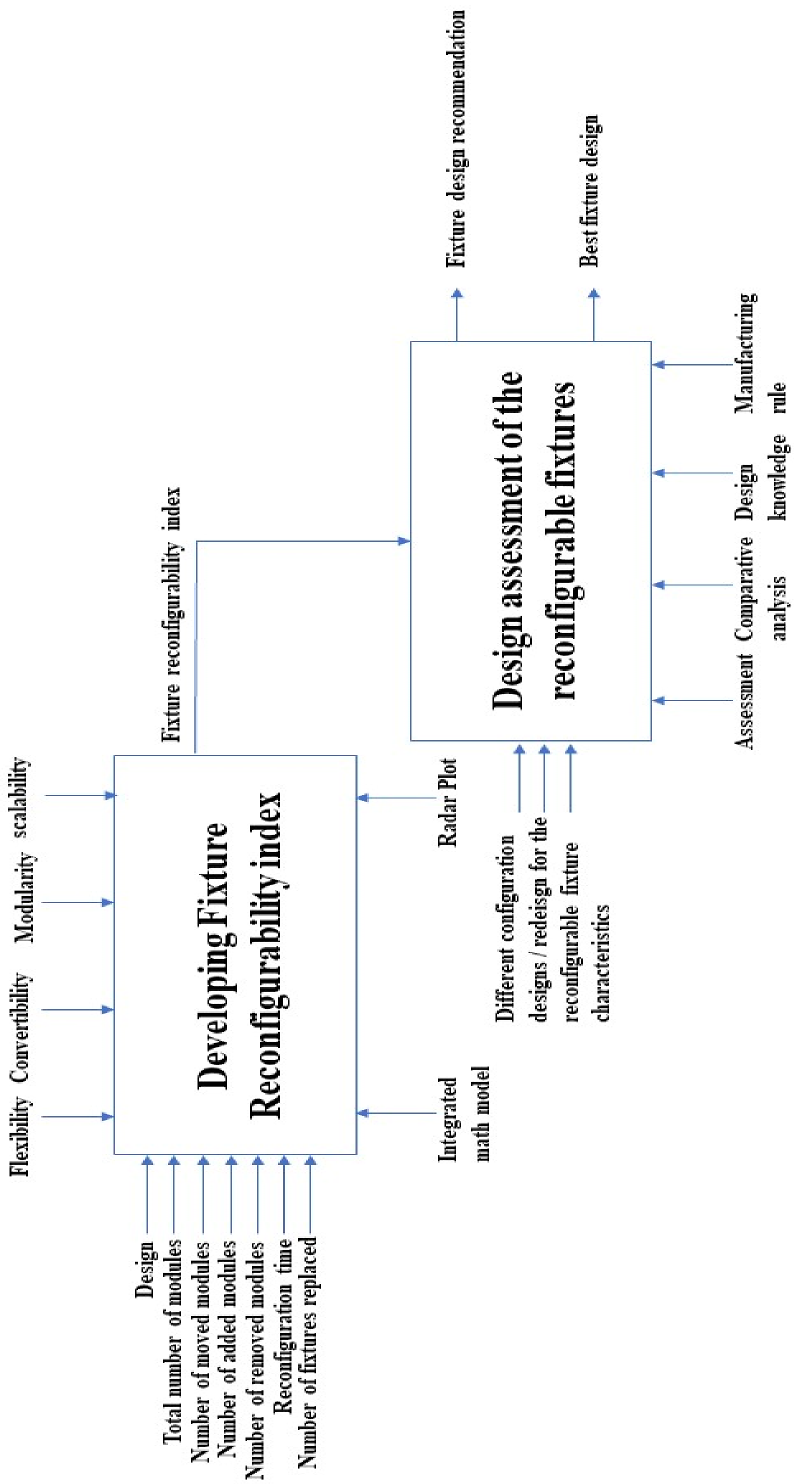


Figure 3.1: IDEF0

The model in this thesis includes two phases. The first phase is developing an index to measure the reconfigurability of the fixtures. The need to measure the reconfigurability due to its importance to reduce reconfiguration time and cost as well as the total time and cost of production is the main reason to use this approach. The input of the first phase includes the main parameters to develop the index. These parameters are the design of the fixture, the total number of modules, the number of replaced modules, the number of added modules, the number of removed modules, the number of moved modules, reconfiguration time, and the number of the fixtures that are replaced. The main factors to control this phase are the four characteristics of the reconfigurable assembly fixtures, which are scalability, flexibility, modularity, and convertibility. The mechanisms that used to develop this index are radar plat and the integrated math models.

The output of the first phase is the fixture reconfigurability index, which controls the second phase of the IDEF0 model. The assessment of various reconfigurable assembly fixtures designs depends on the reconfigurability index because it embodies a measure of the factors influencing it. The input in the second phase is the fixture configuration design. The mechanisms in this phase are comparative analysis, manufacturing rules, design knowledge, and assessment. The output is fixture design recommendations and best fixture design.

3.3 Approach

The mechanism of the assessment is the calculation which is obtained by two methods: 1) Provide quantitative data matrix for reconfigurable assembly fixture evaluation indices by analyzing the meaning of each index and the parameters related to that index, and 2) A method based on a radar plot that is insensitive to the order of the plotting of the individual indices to developed to combine all the indices.

3.3.1 Provide a quantitative data matrix for reconfigurable assembly fixture evaluation indices

- **Convertibility:**

Convertibility is the ability of reconfigurable assembly fixture to quickly transform the functionality of existing modules and controls to suit new production requirements which including the conversion of the functionality of modules within a family to meet the variations.

Since a fixture is a product and a system depending on complexity, approaches to assess the reconfigurability of the system could be used to assess the configurability of fixtures.

Wang et al. (2016) measured and defined the reconfigurability of the system, and his approach to measuring the convertibility depends on the number of modules they need to be adjusted.

Same in measuring the convertibility of the reconfigurable assembly fixtures, the main parameter influences the convertibility of the reconfigurable assembly fixtures are the number of modules that need to be adjusted.

The convertibility is measured as:

$$C = \frac{1}{S_s * (\frac{1}{N_P} \sum_{i=1}^{N_P} N_a + N_r + N_{rp} + N_m)} \quad \text{……………………………………………………3.1}$$

Where C refers to the convertibility of the reconfigurable assembly fixture, which ranges from 0 to 1, with a value closer to 1 indicating a stronger convertibility for the assembly fixture and, conversely, a weaker convertibility. N_a, N_r, N_{rp} and N_m respectively denote the number of modules that need to be added, removed, replaced, or moved. S_s is a similarity coefficient between the parts family in the conversion. N_p denotes to the number of types of parts in the part family.

Where

$$S_s = \frac{N_S}{N_T} \quad \text{……………………………………………………………3.2}$$

Where N_s and N_T are the number of components that will not be adjusted during the conversion and total components, respectively.

- **Scalability**

Scalability is the ability of the reconfigurable assembly fixture to be modified to produce different variants of the fixture family by adding, removing, or replacing some modules.

The scalability is measured by the amount of adjustment required in response to produce different variants of the fixture family.

The scalability is determined by the equation below:

Adjustment + scalability = 1

This equation shows that when the fixture almost satisfies the variants of fixture family. The scalability is high, but if it needs large adjustments, then the scalability is low.

The scalability is measured as:

$$S = 1 - \sum_{i=1}^{N_p} \frac{\frac{N_{a/r}}{N_T} * \frac{T_{rec}}{T_T}}{N_p} \quad \ldots\ldots 3.3$$

Where S refers to the scalability of the reconfigurable assembly fixture, which is a dimensionless value that falls within the range of 0–1, with a near-1 value indicating higher scalability and a near-0 value indicating a lower scalability or even no scalability. $N_{a/r}$ and N_T are the number of modules added, removed or replaced, and the total number of modules, respectively. N_p denotes to the number of types of parts in the part family. T_{rec} and T_T are the reconfiguration time for the reconfigurable assembly fixture and the reconfiguration time (changeover time) of the entire fixture, respectively.

- **Modularity**

Modularity is the ability to modularly rearrange the modules in a fixture for various applications (Erdem, 2017).

Measure the modularity of the fixture as the ratio of the number of standard modules to the total number of modules (Erdem, 2017).

$$M = \frac{N_{st}}{N_T} \quad \text{3.4}$$

Where M refers to the modularity of the reconfigurable assembly fixture, which falls between 0 and1. The index for M closer to 1 indicates higher modularity. Otherwise, the modularity is lower. N_{st} is the number of standard modules which means they will not be changed or replaced to produce different components and N_T is the total number of modules in a reconfigurable assembly fixture.

- **Customization flexibility**

Customization flexibility is the ability of the fixture to adapt to various products and processes within the parts' family (Erdem, 2017). Erdem (2017) defined customized flexibility, but the mathematical model to measure the customized flexibility based on this definition is proposed in this thesis.

The flexibility customization is measured as:

$$C_f = 1 - \frac{1}{N_f} \quad \text{3.5}$$

Where C_f refers to the customization flexibility of the reconfigurable assembly fixture. N_f refers to the number of fixtures that are replaced.

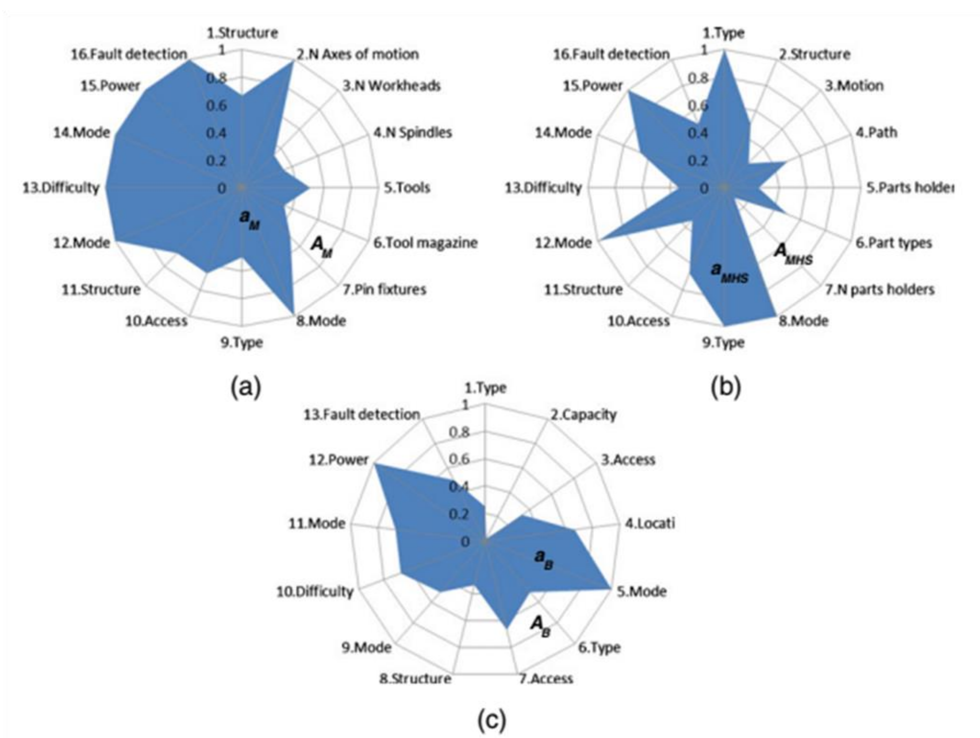
Each characteristic in reconfigurable assembly fixture has a dimensionless value that falls within the range of 0–1, with a near-1 value indicating a higher value of this feature and a near-0 value indicating a lower value.

3.3.2 Combining all the indices using radar plot

It is essential to mention that the weight of each characteristic should be considered based on the importance of each one in a given situation. In this research, it is assumed that the weight of the four characteristics (convertibility, modularity, customized flexibility and scalability) is equal because of the need to find the best fixture design based on the reconfigurability based on all the characteristics equally.

A method based on a radar plot that is insensitive to the order of the plotting of individual indices is developed to combine all the indices and develop the integrated fixture reconfigurability index.

Samy and ElMaraghy (2012) measured the complexity of automated and hybrid assembly systems using the radar plot. Their approach combined the indices by using the radar plot, as shown in figure 3.2, and used the total shaded area to determine the complexity index, which is the ratio of the shaded area to the total area.



Radar plot SCC digits representation: **a** machine, **b** MHS, **c** buffer

Figure 3.2: Examples of radar plot presented by Samy and ElMaraghy (2012)

The same method could be used to measure the reconfigurability of the reconfigurable assembly fixtures.

Therefore, a reconfigurability index is defined as the ratio between the shaded area and the total plot area. The larger shaded area refers to a higher reconfigurability index. The shaded area of the radar plot is the summation of individual triangles as:

$$a = \frac{1}{2}\left[(C_1 * C_4) + \sum_{i=1}^{i=3}(C_i * C_{i+1})\right] sin\left(\frac{360}{4}\right) \quad \text{......} \; 3.6$$

a is the shaded radar plot area. C_i is the normalized code index on the radial axis of digit *i* for each radar plot.

The total radar plot area is given by:

$$A = \left(\frac{4}{2}\right) \sin\left(\frac{360}{4}\right) \quad \text{......} \; 3.7$$

A is the total radar plot area. Then, the reconfigurability index, R, for each class is calculated by dividing both shaded and radar plot areas.

$$R = \frac{a}{A} \quad \text{......} \; 3.8$$

Therefore, the index of the reconfigurability index for any fixture is between 0 and 1.

In this calculation of the integrated reconfigurability index, it is assumed that all individual characteristics are equally important.

3.4 Illustrative Examples

Illustrative examples to collect all the presented information and to understand the challenge, the scope of research, and the expected results of this research are provided.

3.4.1 Reconfigurable assembly fixture for press brakes

An example is adapted from Olayinka et al. (2014) for illustration purposes.

3.4.1.1 Introduction about the example

The method to design reconfigurable fixture is presented for the press brake by Olayinka et al. (2014). The RAF is designed to secure and position the press brake framework with four fingers that are moved by four hydraulic cylinders (finger cylinder). Two hydraulic cylinder which differs in sizes from the finger cylinder also moves the moving frame. The press breaks with minimum, and the maximum width of 1500 mm and 2900 mm can be assembled for reconfigurable assembly fittings. The minimal and maximum lengths of the press brakes which are mounted on it are between 1500 and 5500 mm.

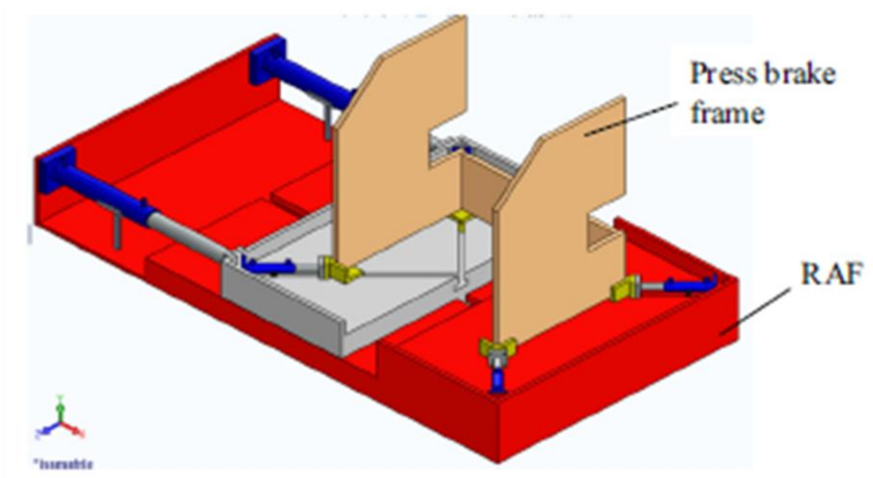


Figure 3.3: Isometric view of the RAF gripping a press brake frame adopted by Olayinka et al. (2014)

Table 3.1: Description of Figure 3.4 RAF parts

The component	Number of components	Description
1	2	Movable frame cylinder
2	2	Movable frame support
3	1	Movable frame
4	1	Fixed frame
5	4	Finger cylinder support
6	4	Hydraulic hose supplying the finger cylinder from the pump
7	4	Finger cylinder
8	4	Fingers
9	2	Hydraulic hose supplying the movable frame cylinder from the pump

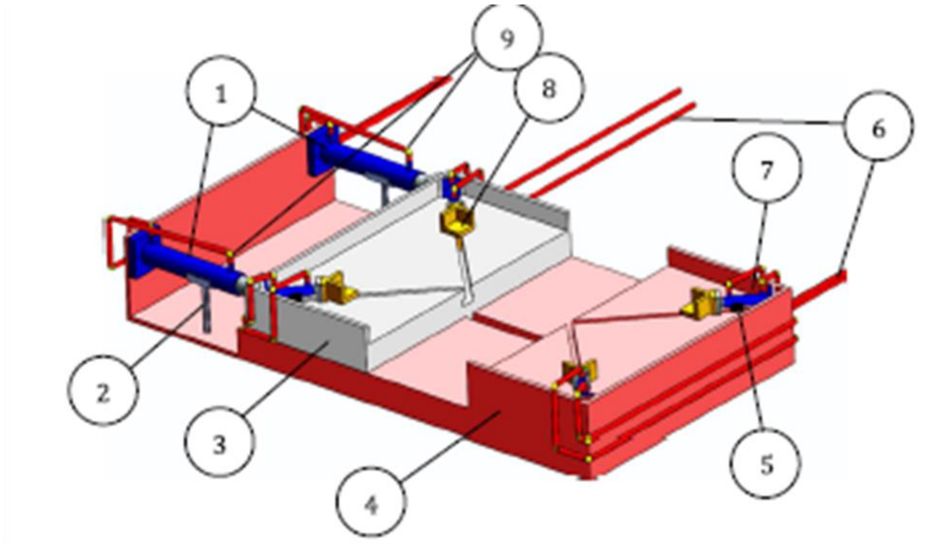


Figure 3.4: Isometric view of the reconfigurable assembly fixture to show the components presented in table 3.1 adopted by Olayinka

3.4.1.2 Measuring the reconfigurability of the press brake fixture

- **Modularity:**

To calculate the modularity, equation 3.4 is used:

$$M = \frac{N_{st}}{N_T}$$

N_{st} = 24 (the number of standard modules that will not be removed or replaced for different product components).

N_T = 24 (the total number of modules in the reconfigurable assembly fixture).

$$M = \frac{24}{24}$$

$$M = 1$$

- **Customization flexibility:**

To calculate the flexibility, equation 3.5 is used:

$$C_f = 1 - \frac{1}{N_f}$$

N_f = 3 (the number of fixtures that are replaced).

$$C_f = 1 - \frac{1}{3}$$

$$C_f = 0.667$$

- **Scalability:**

To calculate the scalability, equation 3.3 is used:

$$S = 1 - \sum_{i=1}^{N_p} \frac{\frac{N_{a/r}}{N_T} * \frac{T_{rec}}{T_T}}{N_p}$$

$N_{a/r}$= 0

N_T = 24 (the total number of modules in the reconfigurable assembly fixture).

N_p = 3

T_{rec}= 10 sec for the replacement of 10cm.

$$S = 1 - \frac{0}{72}$$

$$S = 1$$

- **Convertibility:**

To calculate the convertibility, equations 3.1 and 3.2 are used:

$$C = \frac{1}{S_s * (\frac{1}{N_P}\sum_{i=1}^{N_P} N_a + N_r + N_{rp} + \ N_m)}$$

$N_a = 0$

$N_r = 0$

$N_p = 3$

$N_{rp} = 0$

$N_m = 13$

N_s = 11 (The number of modules that will not be adjusted during the conversion).

$$S_s = \frac{11}{24}$$

S_s =0.458

$$C = \frac{1}{0.4583 * 13}$$

$C = \ 0.168$

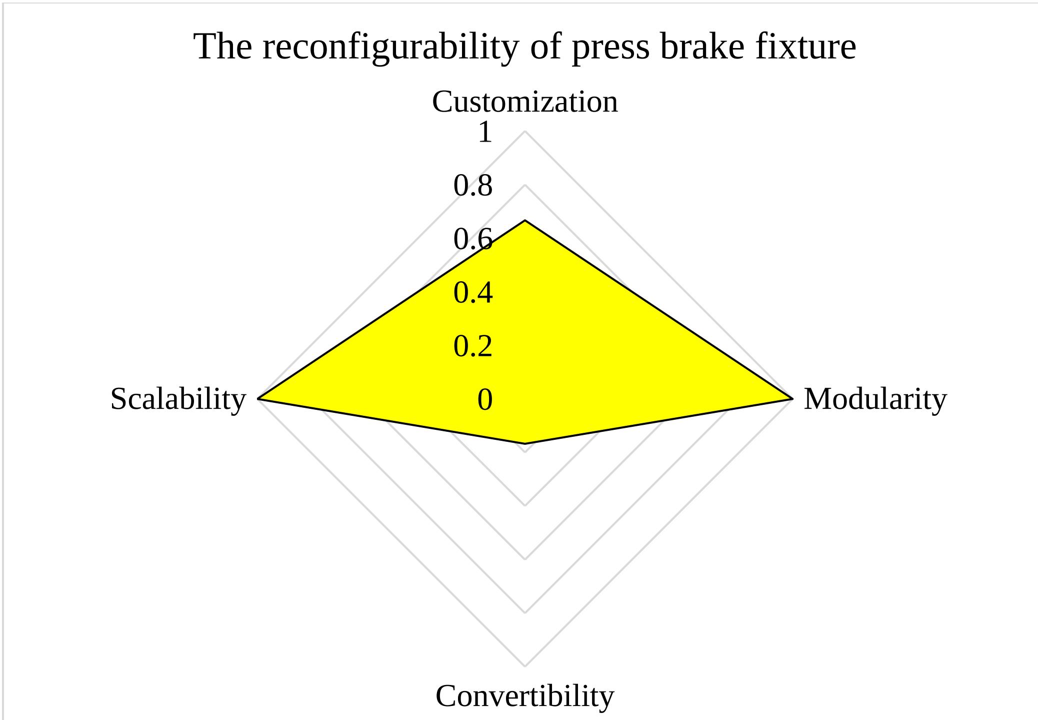


Figure 3.5: The radar chart of the reconfigurable indices of press brake fixture

Figure 3.5 shows that the highest index from the measurement is scalability and modularity; they both equal to 1. The highest index of scalability means the adjustment of the assembly fixture to reconfigure is meager because it is adaptable to the size of the frame with minimum and the maximum width of 1500 mm and 2900 mm and minimum and maximum lengths of the press breaks of 1500 and 5500 mm. Besides, all the modules are standards, which means they will not be changed to produce different frames with minimum and maximum width of 1500 mm and 2900 mm and minimum and maximum lengths of the press breaks of 1500 and 5500 mm. On the other hand, the lowest index from the measurement is convertibility.

A reconfigurability index is defined as the ratio between the shaded area and the total plot area. The larger shaded area refers to a higher reconfigurability index. The shaded area of the radar plot is the summation of individual triangles as equation 3.6:

$$a \quad = \frac{1}{2}\left[(C_1 * C_4) + \sum_{i=1}^{i=3}(C_i * C_{i+1})\right] sin\left(\frac{360}{4}\right)$$

a is the shaded radar plot area. C_i is the normalized code index on the radial axis of digit i for each radar plot.

$a = 0.973$

The total radar plot area is given by:

$$A = \left(\frac{4}{2}\right)\sin\left(\frac{360}{4}\right)$$

$A = 2$

A is the total radar plot area. Then, the reconfigurability index, R, for each class is calculated by dividing both shaded and radar plot areas.

$$R = \frac{a_1}{A_1}$$

$$R = \frac{0.973}{2} = 0.486$$

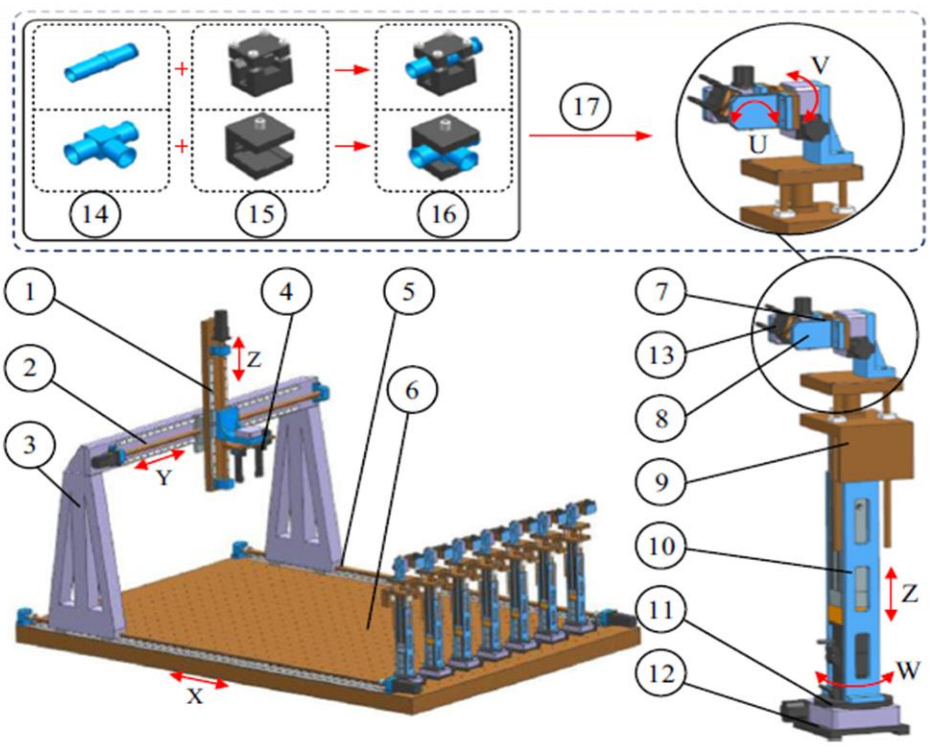
Therefore, the index of reconfigurability for the welding fixture is 0.486.

3.4.2 Reconfigurable assembly fixture for metal sheet

Another example is adapted from Fan et al. (2018) for illustration purposes.

3.4.2.1 Introduction about the example

The method to design reconfigurable fixture is presented for the aerospace pipelines assembly before welding by Fan et al. (2018). This fixture is designed to improve assembly quality for product variants of pipelines before going to the next step, which is welding. This fixture includes three systems; mechanical, configuration, and control system. The components of the mechanical system in this fixture are shown in Figure 3.6.



Composition of the mechanical system: (1) *Z* axis linear prismatic module; (2) *Y* axis linear prismatic module; (3) *X* axis linear prismatic module; (4) Electric gripper; (5) Gantry frame; (6) Workbench; (7) *Y* axis rotary modular; (8) *X* axis rotary modular; (9) Hoisting interface; (10) *Z* axis linear prismatic module; (11) *Z* axis rotary module; (12) Magnetic base; (13) Terminal clamp; (14) Tube joint; (15) Terminal clamp; (16) Assembly of the tube joint and the terminal clamp; (17) Screw fastening

Figure 3.6: Composition of the mechanical system by Fan et al. (2018)

The locator is moved per the GHP configuration principle to the target position. The electromagnetic force produced by the magnetic bases to fix the locator at the workbench. The joints of the tube are position according to the shape of the tube configuration where each joint is positioned to specific pose by locator. Then, the tube is assembled based on the specific configuration, and four lines label the interface of each tube and then disassembled. The steps are shown in Figure 3.7.

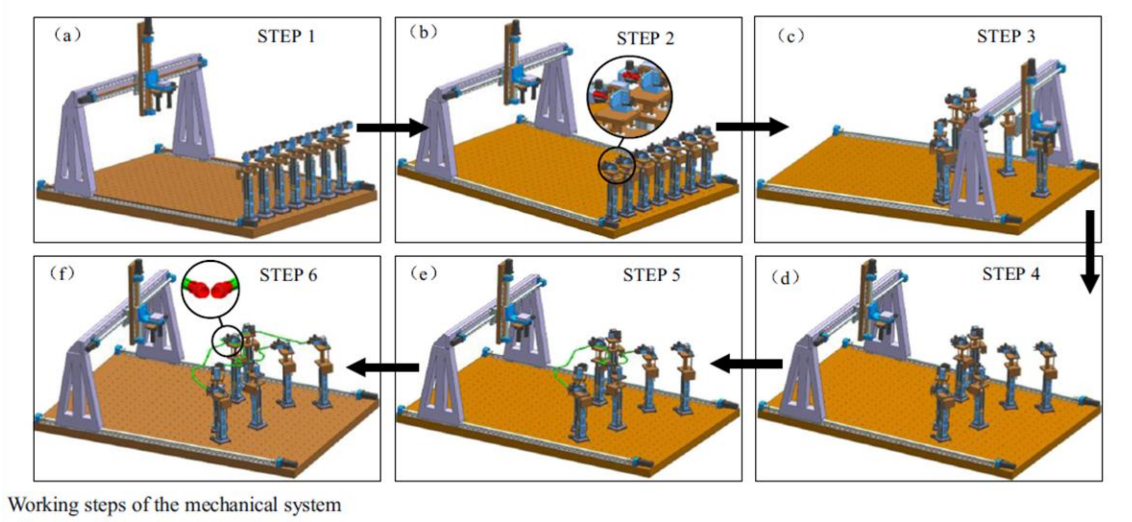


Figure 3.7: Working steps of the mechanical system by Fan et al. (2018)

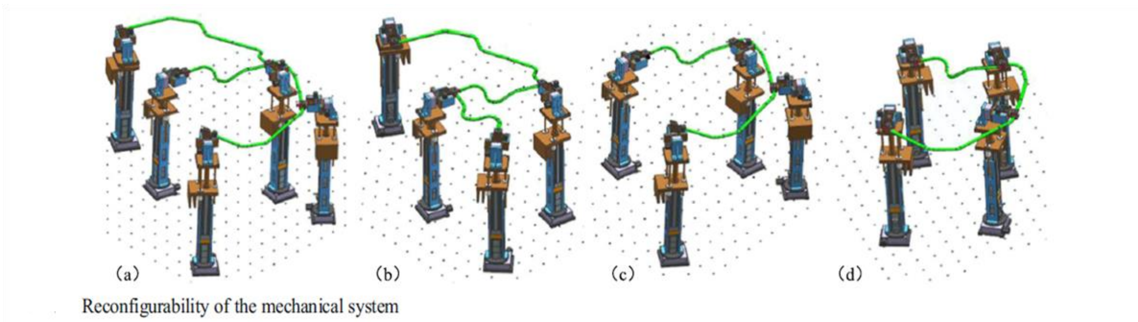


Figure 3.8: Different configurations of the mechanical system by Fan et al. (2018)

3.4.2.2 Measuring the reconfigurability of the metal sheet fixture

- **Modularity:**

To calculate the modularity, equation 3.4 is used:

$$M = \frac{N_{st}}{N_T}$$

N_{st} = 70 (The number of standard modules to assemble six tubes).

N_T = 84 (Total number of modules in the fixture to assemble six tubes)

$M = \frac{70}{84}$

$M = 0.833$

- **Customization flexibility:**

To calculate the flexibility, equation 3.5 is used:

$C_f = 1 - \frac{1}{6}$

N_f= 6 (The maximum number of fixtures that previously used for the same task which assembles six tubes in different shapes)

$C_f = 1 - \frac{1}{6}$

$C_f = 0.833$

- **Scalability:**

To calculate the scalability, equation 3.3 is used:

$$S = 1 - \sum_{i=1}^{N_p} \frac{\frac{N_{a/r}}{N_T} * \frac{T_{rec}}{T_T}}{N_p}$$

$N_{a/r}$= 14 (The number of modules that are replaced to assemble six tubes; 7 for the Tube joints and another 7 for terminal clamps)

$N_T = 84$ (The total number of modules in the fixture to assemble six tubes)

$N_p = 4$ (The number of joint tube types which is equal to the number of the terminal clamps).

T_{rec}= 2 (The whole time reconfiguration process takes about approximately 2 mins from the beginning of the assembly to completion of the tube joint position adjustment).

However, it would approximately take 5 to 8 min for the traditional assembly mode to complete the same work with the aid of high-precision measuring instruments

T_T= 5 to 8 (The time to finish the same job with the help of high-precision measuring instruments in traditional assembly mode).

$S = 0.933$

- **Convertibility:**

To calculate the convertibility, equations 3.1 and 3.2 are used:

$$C = \frac{1}{S_s * (\frac{1}{N_P} \sum_{i=1}^{N_P} N_a + N_r + N_{rp} + \ N_m)}$$

$N_a = 0$

$N_r = 0$

$N_p = 4$

$N_{rp} = 14$ (the number of modules that are replaced (tube joints and terminal clamps)).

$N_m = 37$ (the number of modules that are moved).

N_s = 7 (The number of modules that will not be adjusted during the conversion).

$$S_s = \frac{7}{84}$$

S_s =0.0833

$$C = \frac{1}{0.08333 * (0 + 0 + 37 + 14)}$$

$C = 0.235$

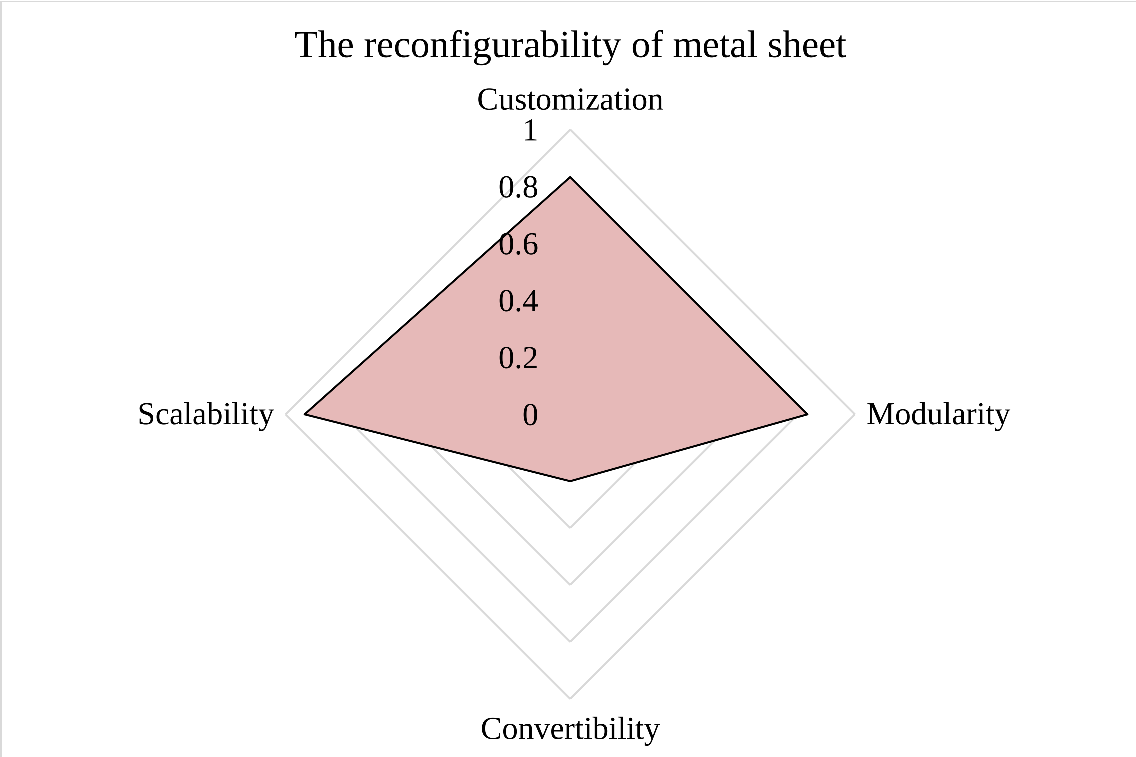


Figure 3.9: The radar chart of the reconfigurability indices of the metal sheet fixture

Figure 3.9 shows that the highest index from the measurement is scalability, modularity, and flexibility. That means this fixture almost satisfies the variants of the part family because the adjustment is meager. On the other hand, the lowest index from the measurement is convertibility, which means it takes time for reconfiguration.

A reconfigurability index is defined as the ratio between the shaded area and the total plot area. The larger shaded area refers to a higher reconfigurability index. The shaded area of the radar plot is the summation of individual triangles as equation 3.6:

$$a = \frac{1}{2}\left[(C_1 * C_4) + \sum_{i=1}^{i=3}(C_i * C_{i+1})\right] sin\left(\frac{360}{4}\right)$$

a is the shaded radar plot area. C_i is the normalized code index on the radial axis of digit i for each radar plot.

$$a = 0.973$$

The total radar plot area is given by:

$$A = \left(\frac{4}{2}\right)\sin(\frac{360}{4})$$

$$A = 2$$

A is the total radar plot area. Then, the reconfigurability index, R, for each class is calculated by dividing both shaded and radar plot areas.

$$R = \frac{a_1}{A_1}$$

$$R = \frac{0.973}{2} = 0.487$$

Therefore, the index of reconfigurability for the welding fixture is 0.487.

3.5 Conclusion

In this chapter, the assessment method of the reconfigurable fixture approach was introduced and applied to reconfigurable assembly fixtures using simple illustrative examples. Those illustrative examples showed the reconfigurability of these fixtures. That helped to present some recommendations to increase the reconfigurability of the fixture. This assessment could be used in the initial phase of a reconfigurable assembly fixture design to choose the most appropriate configuration design of the fixture. Detailed scenarios and comparisons of those recommendations are presented in chapter 4.

CHAPTER 4

CASE STUDY AND RECOMMENDATIONS

4.1 Introduction

In this chapter, assessing the new design configurations of the fixture and comparing it to the previous one before applying some recommendations is presented. The methodology to increase the reconfigurability depends on the four characteristics of the reconfigurable assembly fixture. Increasing the value of each one of them will enhance the reconfigurability of the assembly fixture. Enhancing the reconfigurability is improved through some recommendations that could be applied to the assembly fixture. These recommendations are different from one assembly fixture to another.

The outcome of this chapter was to capture the results of the measurement of the reconfigurable assembly fixture after these recommendations. These results used to compare it with the configuration of the assembly fixture before applying the recommendations.

4.2 Case Study

A detailed example is adapted from Bejlegaard et al. (2018) for illustration purposes.

4.2.1 Introduction about welding tack fixture

The method to design reconfigurable fixture is presented and validated for the welding task by Bejlegaard et al. (2018). This fixture replaced six different dedicated fixtures that were used for the same tasks but different six products.

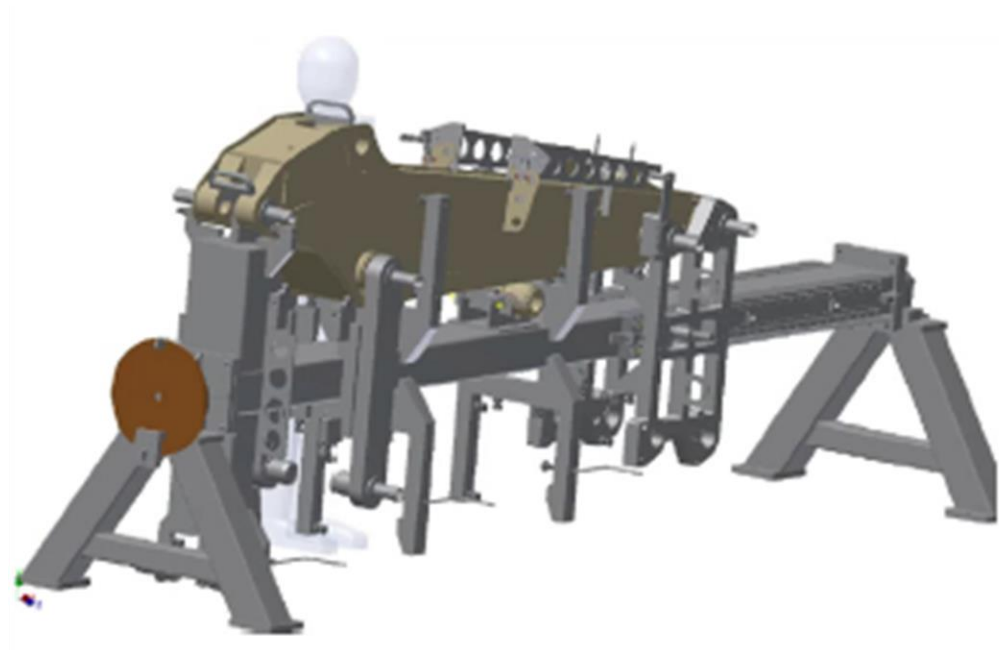


Figure 4.1: Example of one of the existing, dedicated tack-welding fixtures subject to the case study presented by Bejlegaard et al. (2018)

The six different components which are produced using one fixture are shown in figure 4.2.

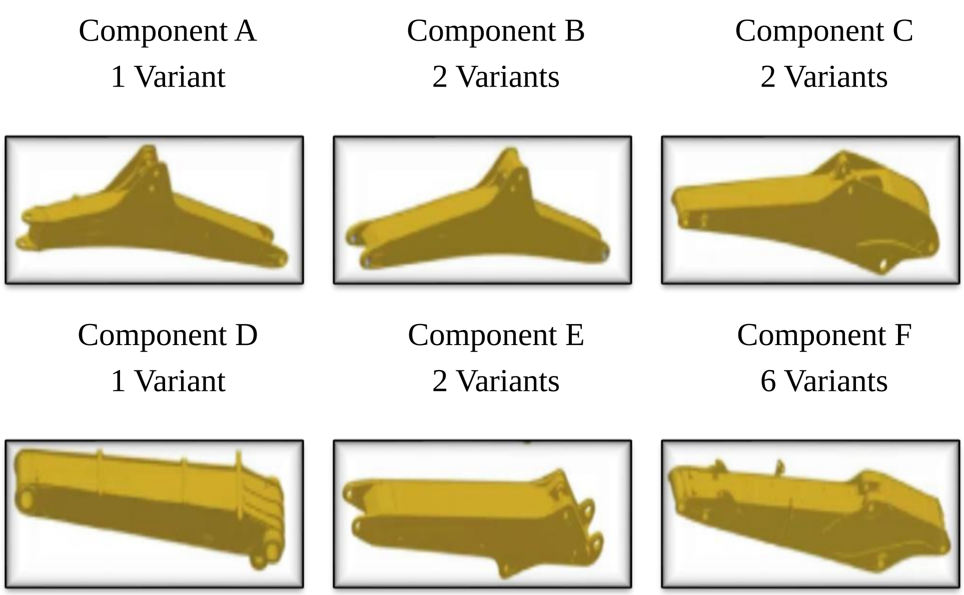


Figure 4.2: Six different components Adopted from Bejlegaard et al. (2018)

Figure 4.3 shows the new reconfigurable fixture by Bejlegaard et al. (2018) which consist of four essential groups indicated in table 4.1:

Table 4.1: The parts in the reconfigurable fixture for welding tack adopted from Bejlegaard et al. (2018)

Platform	Fixture manipulator and beam are the same for all products.
Domain module	Side support 1, side support 2, bottom support and Top support
Product-specific	End stop support
Transport/ support	Front axle support and back axle support

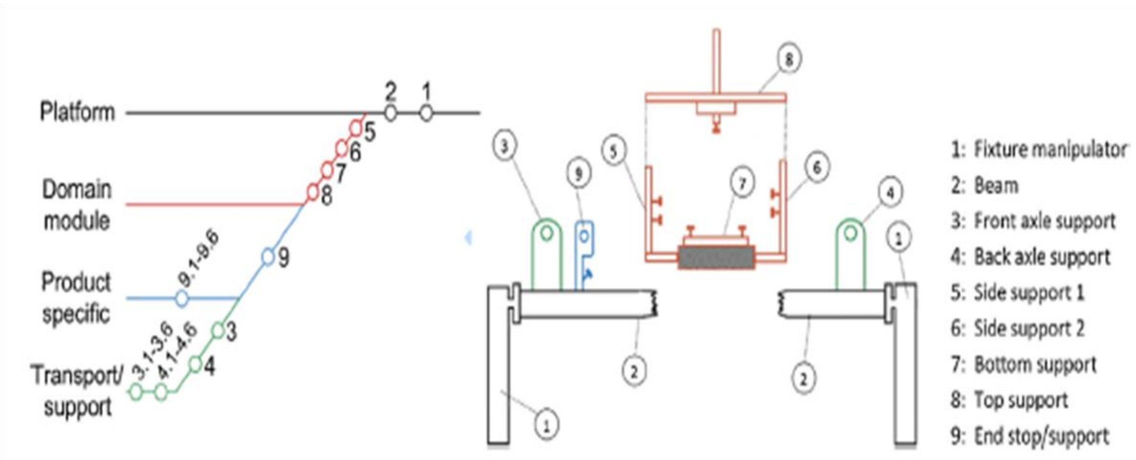


Figure 4.3: Cladistics analysis of the new proposed fixture architecture Adopted by Bejlegaard et al. (2018)

4.2.2 Measuring the reconfigurability of the welding fixture

- **Modularity:**

To calculate the modularity, equation 3.4 is used:

$$M = \frac{N_{st}}{N_T}$$

N_{st} = 6 (the standard modules in the reconfigurable fixture, which means they will not be changed to produce different components).

N_T = 9 (Total modules in the fixture).

$$M = \frac{6}{9}$$

$$M = 0.667$$

- **Customization flexibility:**

To calculate the flexibility, equation 3.5 is used:

$$C_f = 1 - \frac{1}{N_f}$$

N_f= 6 (The number of fixtures that previously required to do the same task).

$$C_f = 1 - \frac{1}{6}$$

$$C_f = 0.833$$

- **Scalability:**

To calculate the scalability, equation 3.3 is used:

$$S = 1 - \sum_{i=1}^{N_p} \frac{\frac{N_{\frac{a}{r}}}{N_T} * \frac{T_{rec}}{T_T}}{N_p}$$

$N_{a/r}$= 3 (two every time a new component is produced and one different types of product components within the family).

N_T = 9 (Total number of the modules in reconfigurable assembly fixture)

N_p = 6 (The number of components)

T_{rec}= 10 min. The time needed to change 1-3 modules (Bejlegaard et al., 2018).

T_T=45 min. The time needed to change the entire fixture (Bejlegaard et al., 2018).

$$S = 1 - \frac{(3 \ + 3 + \ 3 + 3 + 3 + 3) * 10}{9 * 6 * 45}$$

$$S = 0.926$$

- **Convertibility:**

To calculate the convertibility, equations 3.1 and 3.2 are used:

$$C = \frac{1}{S_s * (\frac{1}{N_P} \sum_{i=1}^{N_P} N_a + N_r + N_{rp} + N_m)}$$

$N_a = 0$

$N_r = 0$

$N_p = 6$ (The number of components)

$N_{rp} = 3$ (two every time a new component is produced and one different types of product components within the family).

$N_m = 4$ (The number of models that are moved for each configuration)

N_s = 2 (The number of modules that will not be adjusted during the conversion).

$$S_s = \frac{N_s}{N_T}$$

$$S_s = \frac{2}{9}$$

$$S_s = 0.222$$

$$C = \frac{1}{0.222 * (7)}$$

$$C = 0.643$$

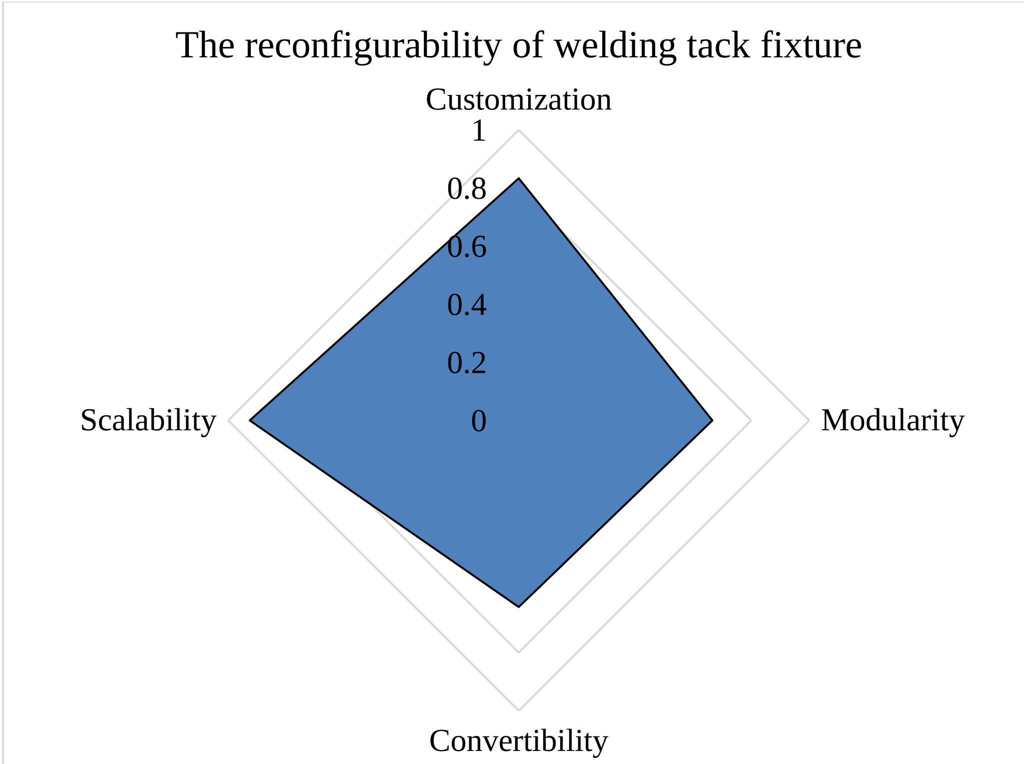


Figure 4.4: The radar chart of the reconfigurable indices of welding fixture

Figure 4.4 shows that the highest index from the measurement is scalability because the adjustment of the assembly fixture to reconfigure is very low, which means that this design configuration of the assembly fixture satisfies to produce the six components with low adjustment. On the other hand, the lowest index from the measurement is convertibility.

A reconfigurability index is defined as the ratio between the shaded area and the total plot area. The larger shaded area refers to a higher reconfigurability index. The shaded area of the radar plot is the summation of individual triangles as equation 3.6:

$$a \quad = \frac{1}{2}\left[(C_1 * C_4) + \sum_{i=1}^{i=3}(C_i * C_{i+1})\right] sin\left(\frac{360}{4}\right)$$

a is the shaded radar plot area. C_i is the normalized code value on the radial axis of digit *i* for each radar plot.

$a = 1.176$

The total radar plot area is given by:

$$A = \left(\frac{4}{2}\right)\sin(\frac{360}{4})$$

$$A = 2$$

A is the total radar plot area. Then, the reconfigurability index, R, for each class is calculated by dividing both shaded and radar plot areas as equation 3.8:

$$R = \frac{a}{A}$$

$$R = \frac{1.176}{2} = 0.588$$

Therefore, the index of **reconfigurability for the welding fixture is 0.588.**

4.2.3 Redesign of welding tack fixture

The redesign recommendation focused on the convertibility of the fixture, which equals 0.64 because it has the lowest index compared to the other characteristics. To increase the convertibility here is some recommendations:

a) Separate the top support, which is shown in figure 4.5 and the rest of the domain module or remove it.

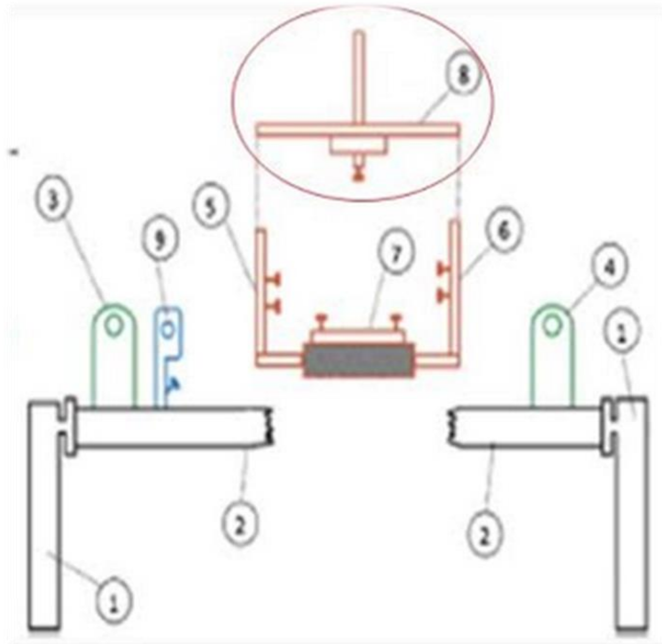


Figure 4.5: Top support is circled

b) Combine side support 1, bottom support, and side support 2 and remove the top support, as shown in figure 4.6.

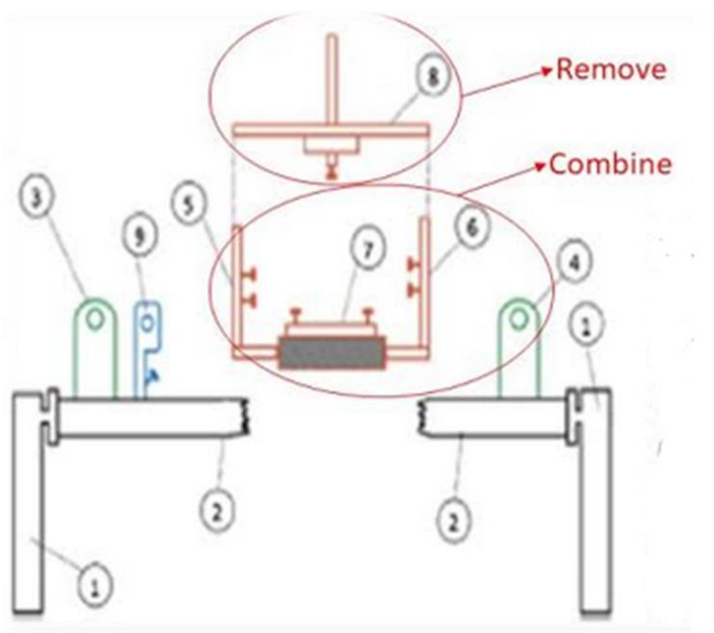


Figure 4.6: Side support, bottom support, and side support 2 (combined), Top support (removed) are circled

4.2.3.1 First recommendation on the welding task fixture

Separate the top support and the rest of the domain module or remove it.

- **Modularity:**

To calculate the modularity, equation 3.4 is used:

$$M = \frac{N_{st}}{N_T}$$

N_{st} = 5 (the standard modules in the reconfigurable fixture, which means they will not be changed to produce different components; the value becomes five because the top support is removed).

N_T = 8 (Total modules in the fixture, the value becomes eight because the top support is removed).

$$M = \frac{5}{8}$$

$$M = 0.625$$

- **Customization flexibility:**

To calculate the flexibility, equation 3.5 is used:

$$C_f = 1 - \frac{1}{N_f}$$

N_f = 6 (The number of fixtures that previously required to do the same task).

$$C_f = 1 - \frac{1}{6}$$

$$C_f = 0.833$$

- **Scalability:**

To calculate the scalability, equation 3.3 is used:

$$S = 1 - \sum_{i=1}^{N_p} \frac{\frac{N_{\frac{a}{r}}}{N_T} * \frac{T_{rec}}{T_T}}{N_p}$$

$N_{a/r}$= 3 (two every time a new component is produced and one different types of product components within family)

$N_T = 8$ (Total number of the modules in reconfigurable assembly fixture; the value becomes eight because the top support is removed).

$N_p = 6$ (The number of product components)

T_{rec}= 10 min. The time needed to change 1-3 modules (Bejlegaard et al., 2018).

T_T=45 min. The time needed to change the entire fixture (Bejlegaard et al., 2018).

$$S = 1 - \frac{(3 + 3 + 3 + 3 + 3 + 3) * 10}{8 * 6 * 45}$$

$S = 0.917$

- **Convertibility:**

To calculate the convertibility, equations 3.1 and 3.2 are used:

$$C = \frac{1}{S_s * (\frac{1}{N_P} \sum_{i=1}^{N_P} N_a + N_r + N_{rp} + N_m)}$$

$N_a = 0$

$N_r = 0$

$N_p = 6$ (The number of product components)

$N_{rp} = 3$ (The number of models that are replaced; two every time a new component is produced and one different types of product components within family).

$N_m = 3$ (The number of models that are moved for each configuration)

$$S_s = \frac{N_s}{N_T}$$

$$S_s = \frac{2}{8}$$

$$S_s = 0.25$$

$$C = \frac{1}{0.25 * (6)}$$

$$C = 0.667$$

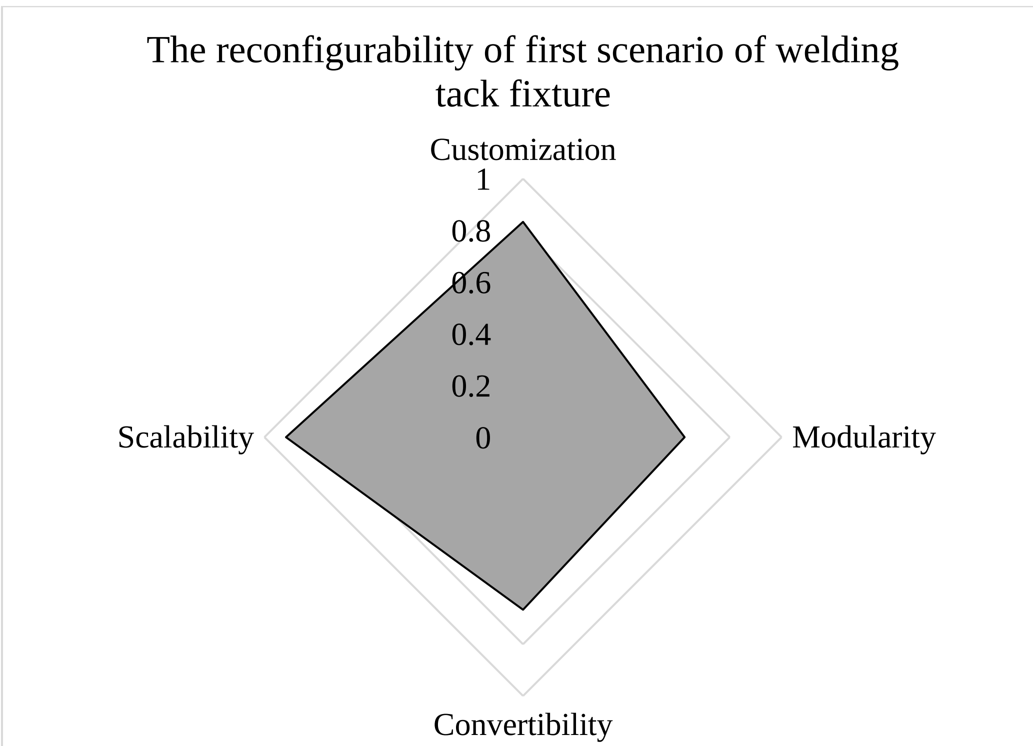


Figure 4.7: The radar chart for welding fixture after the first recommendation

Figure 4.7 shows that the highest index from the measurement is scalability because the adjustment of the assembly fixture to reconfigure is very low, which means that this design configuration of the assembly fixture satisfies the six components with low adjustment. The convertibility is still low even with removing one module because the fixture has more six modules moved or replaced for different configurations.

A reconfigurability index is defined as the ratio between the shaded area and the total plot area. The larger shaded area refers to a higher reconfigurability index. The shaded area of the radar plot is the summation of individual triangles as equation 3.6:

$$a \quad = \frac{1}{2}\left[(C_1 * C_4) + \sum_{i=1}^{i=3}(C_i * C_{i+1})\right] sin\left(\frac{360}{4}\right)$$

a is the shaded radar plot area. C_i is the normalized code value on the radial axis of digit *i* for each radar plot.

$a = 1.154$

The total radar plot area is given by:

$$A = \left(\frac{4}{2}\right)\sin\left(\frac{360}{4}\right)$$

$A = 2$

A is the total radar plot area. Then, the reconfigurability index, R, for each class is calculated by dividing both shaded and radar plot areas as equation 3.8:

$$R = \frac{a}{A}$$

$$R = \frac{1.187}{2} = 0.577$$

Therefore, the index of **reconfigurability for the first welding fixture re-design is 0.577.**

4.2.3.2 Second recommendation on the welding tack fixture

Combine side support 1, bottom support, and side support 2 and remove the top support, as shown in figure 4.6.

- **Modularity:**

To calculate the modularity, equation 3.4 is used:

$$M = \frac{N_{st}}{N_T}$$

N_{st} = 4 (the standard modules in the reconfigurable fixture which means they will not be changed to produce different components; the value becomes four because side support 1, bottom support and side support two are combined, and top support is removed).

N_T = 6 (Total modules in the fixture; the index becomes six because side support 1, bottom support, and side support two are combined; and top support is removed).

$$M = \frac{4}{6}$$

$$M = 0.667$$

- **Customization flexibility:**

To calculate the flexibility, equation 3.5 is used:

$$C_f = 1 - \frac{1}{N_f}$$

N_f = 6 (The number of fixtures that previously required to do the same task).

$$C_f = 1 - \frac{1}{6}$$

$$C_f = 0.833$$

- **Scalability:**

To calculate the scalability, equation 3.3 is used:

$$S = 1 - \sum_{i=1}^{N_p} \frac{\frac{N_{\frac{a}{r}}}{N_T} * \frac{T_{rec}}{T_T}}{N_p}$$

$N_{a/r}$= 3 (2 every time a new component is produced and one different types of product components within the family).

$N_T = 6$ (Total number of the modules in reconfigurable assembly fixture; the index becomes six because side support 1, bottom support and side support two are combined, and top support is removed)

$N_p = 6$ (The number of product components)

T_{rec}= 10 min. The time needed to change 1-3 modules (Bejlegaard et al., 2018).

T_T=45 min. The time needed to change the entire fixture (Bejlegaard et al., 2018).

$$S = 1 - \frac{(3 + 3 + 3 + 3 + 3 + 3) * 10}{6 * 6 * 45}$$

$S = 0.889$

- **Convertibility:**

To calculate the convertibility, equations 3.1 and 3.2 are used:

$$C = \frac{1}{S_S * (\frac{1}{N_P} \sum_{i=1}^{N_P} N_a + N_r + N_{rp} + N_m)}$$

$N_a = 0$

$N_r = 0$

$N_p = 6$

N_{rp} = 3 (The number of models that are replaced; two every time a new component is produced and one different types of product components within family).

N_m = 1 (The number of models that are moved for each configuration)

$$S_s = \frac{N_s}{N_T}$$

$$S_s = \frac{2}{6}$$

$$S_s = 0.333$$

$$C = \frac{1}{0.33 * (4)}$$

$$C = 0.750$$

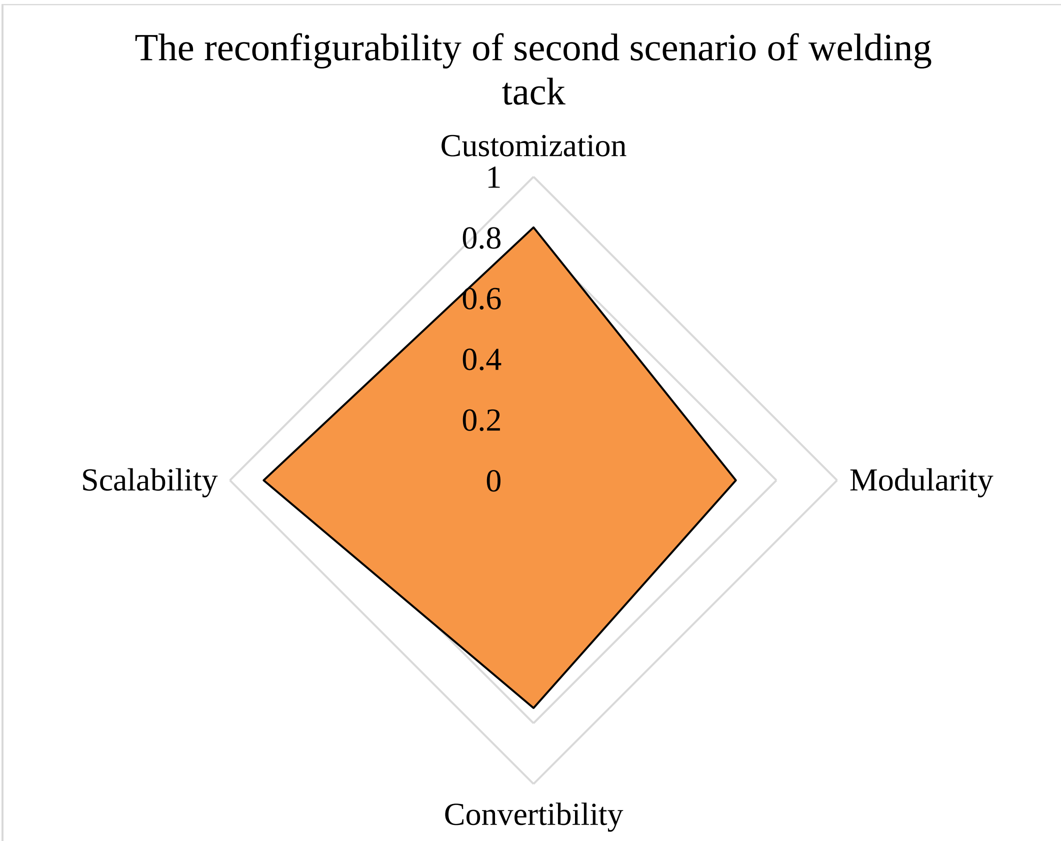


Figure 4.8: The radar chart for welding fixture after the second recommendation

Figure 4.8 shows that the highest index from the measurement is scalability because the adjustment of the assembly fixture to reconfigure is very low, which means that this design configuration of the assembly fixture satisfies the six components with low adjustment and with fewer modules in the assembly fixture.

A reconfigurability index is defined as the ratio between the shaded area and the total plot area. The larger shaded area refers to a higher reconfigurability index. The shaded area of the radar plot is the summation of individual triangles as equation 3.6:

$$a \quad = \frac{1}{2}\left[(C_1 * C_4) + \sum_{i=1}^{i=3}(C_i * C_{i+1})\right] sin\left(\frac{360}{4}\right)$$

a is the shaded radar plot area. C_i is the normalized code index on the radial axis of digit *i* for each radar plot.

$a = 1.229$

The total radar plot area is given by:

$$A = \left(\frac{4}{2}\right)\sin(\frac{360}{4})$$

$A = 2$

A_1 is the total radar plot area. Then, the reconfigurability index, R, for each class is calculated by dividing both shaded and radar plot areas as equation 3.8:

$$R = \frac{a}{A}$$

$$R = \frac{1.229}{2} = 0.615$$

Therefore, the index of **reconfigurability for the second welding fixture redesign is 0.615.**

4.3 Discussion

The results derived from the analysis of the case study and two redesign recommendations are summarized in the following table 4.2 and illustrated in subsequent discussion and figures.

Table 4.2: The results derived from the analysis of the case study and two redesign recommendations

	Modularity	Customized Flexibility	Scalability	Convertibility	Re-configurability
Original fixture design	0.667	0.833	0.926	0.643	0.588
Redesign 1	0.625	0.833	0.917	0.667	0.577
Redesign 2	0.667	0.833	0.889	0.750	0.615

Figure 4.9 shows the scalability for three scenarios. It can be seen that the scalability of the example without any of these redesign recommendations is the highest because the ratio between the number of modules that are replaced to the total number of modules in the assembly fixture is higher than the other two redesign recommendations.

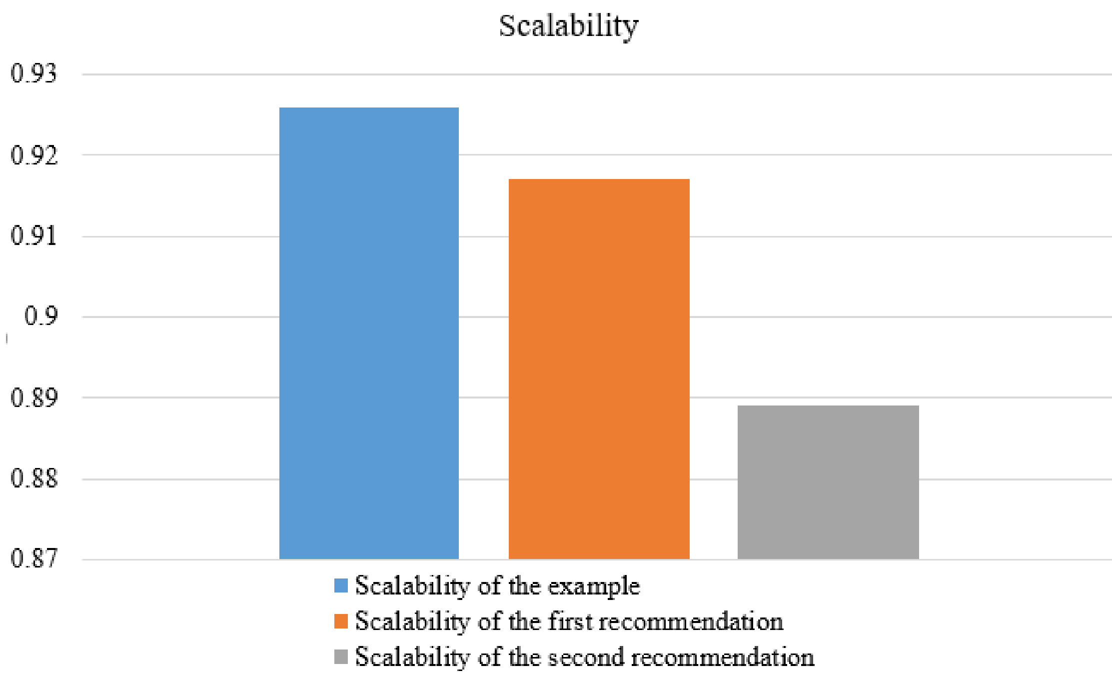


Figure 4.9: The differences between the primary example and the two redesign recommendations in scalability

On the other hand, it can be seen that there is improvement in convertibility after applying some recommendations on the assembly fixture. The convertibility of the second redesign recommendation is higher than the primary example and the first redesign recommendation on the example, as shown in Figure 4.10, because the total number of modules and also the number of modules that moved in the second redesign recommendation example become less.

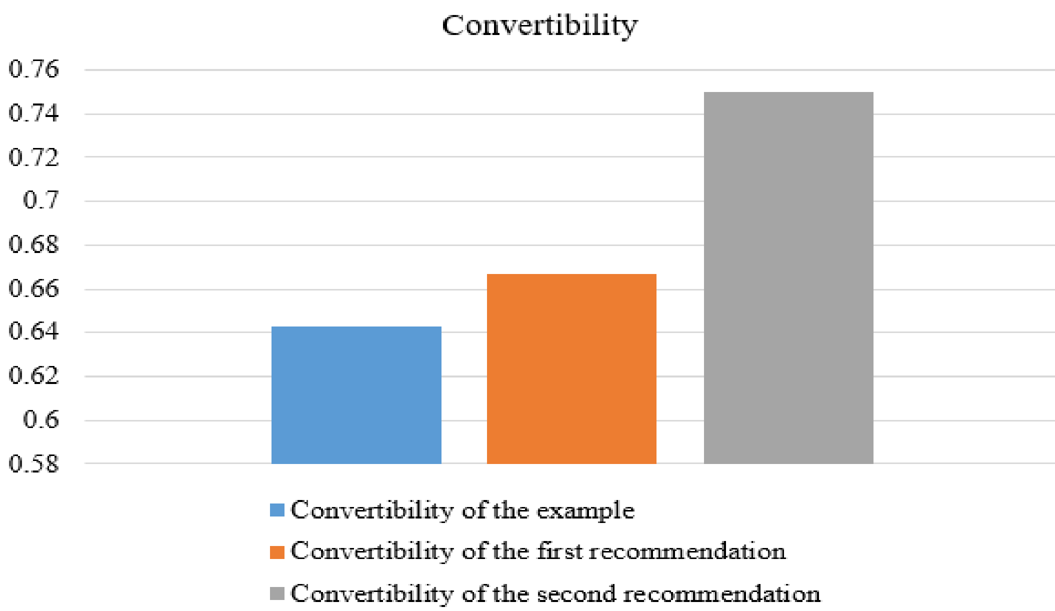


Figure 4.10: The differences between the primary example and the two redesign recommendations in convertibility

Figure 4.11 shows the modularity for the primary example, and the second redesign recommendation is the same, but the modularity for the primary example is different from the first redesign recommendation because the one standard module was removed.

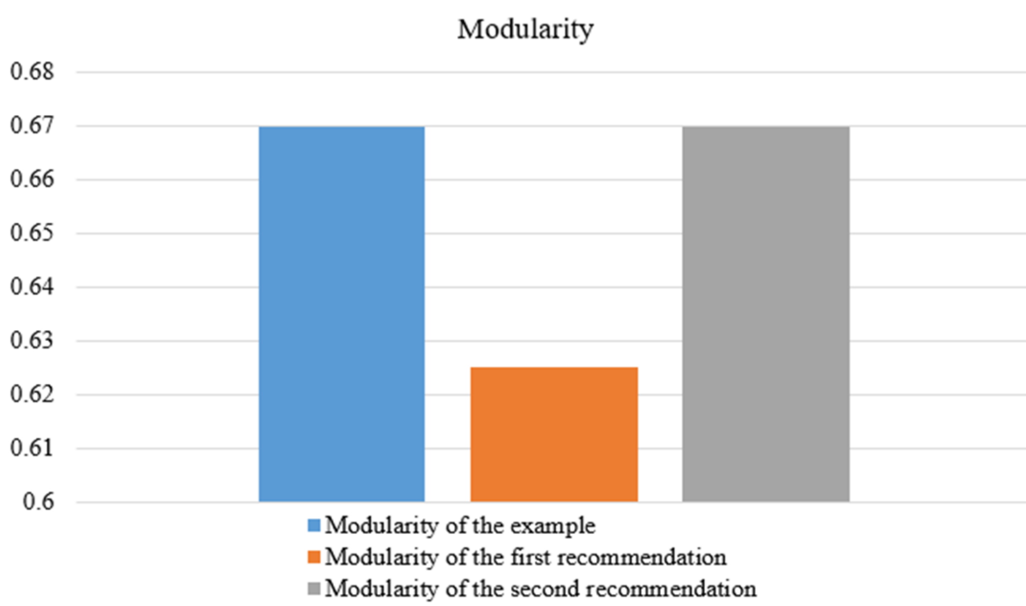


Figure 4.11: The differences between the primary example and the two redesign recommendations in modularity

The index of the customized flexibility for all is the same as shown in figure 4.12 because the number of fixtures that this fixture is replaced for is the same for all design configurations.

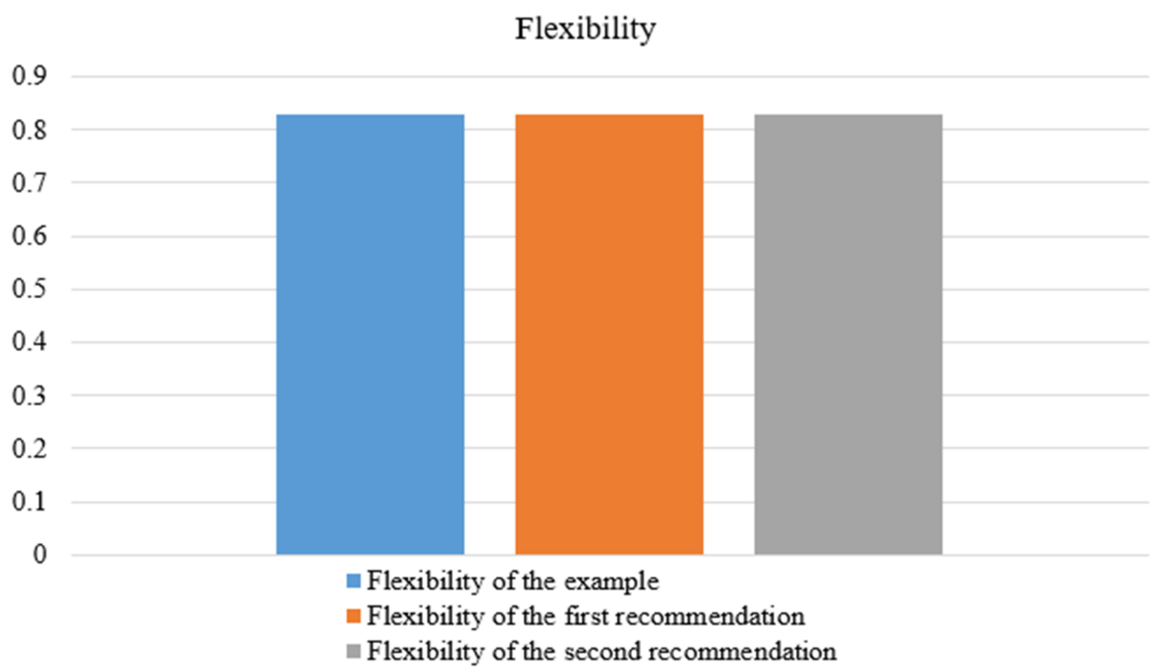


Figure 4.12: The differences between the primary example and the two redesign recommendations in Customization flexibility

Figure 4.13 shows the differences between the reconfigurability of three design configurations. The second redesign configuration has the highest index of the reconfigurability. Moreover, this figure shows the enhancement of the reconfigurability when some recommendations are applied to the design.

The highest reconfigurability index is 0.615, which is higher than the reconfigurability index for the first redesign recommendation, which is 0.577.

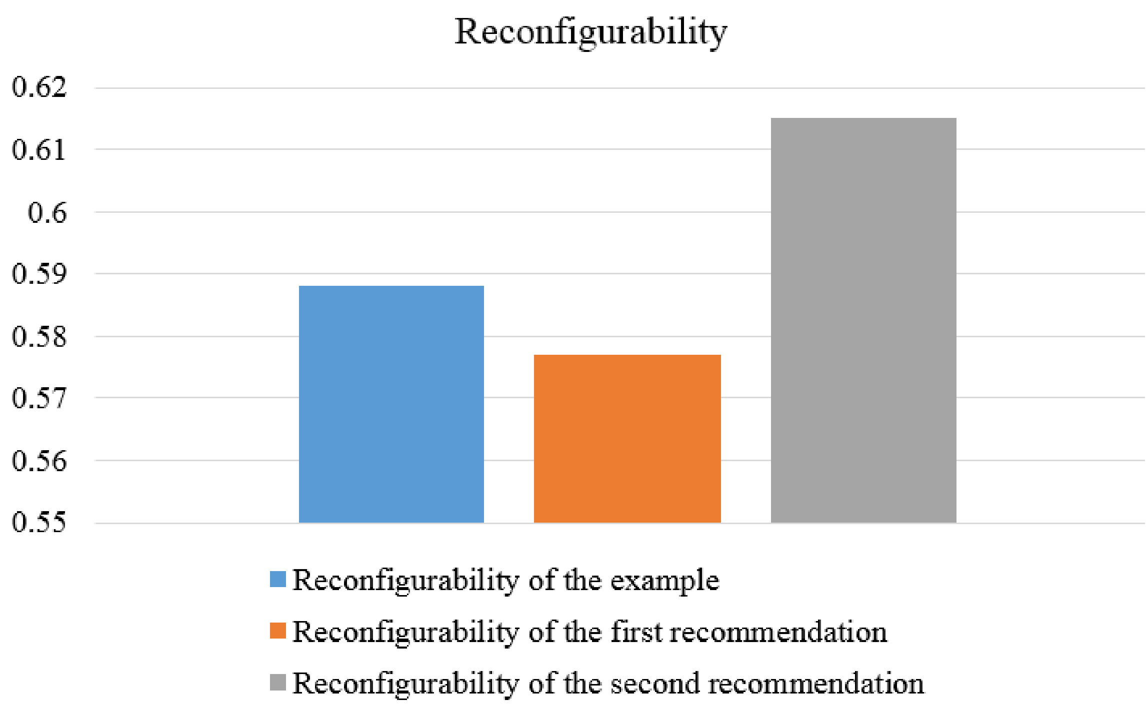


Figure 4.13: The differences between the primary example and the two recommendations in Reconfigurability

These recommendations help to improve the reconfigurability of the fixture for the reusability and less cost. The improvement for reconfigurability for the second recommendation is 5% higher than the reconfigurability of the primary example and 7% than the reconfigurability of the first redesign recommendation.

Despite the increase of convertibility, the reconfigurability index of the first recommendation design is lower than the primary example because the index of modularity and scalability decreased.

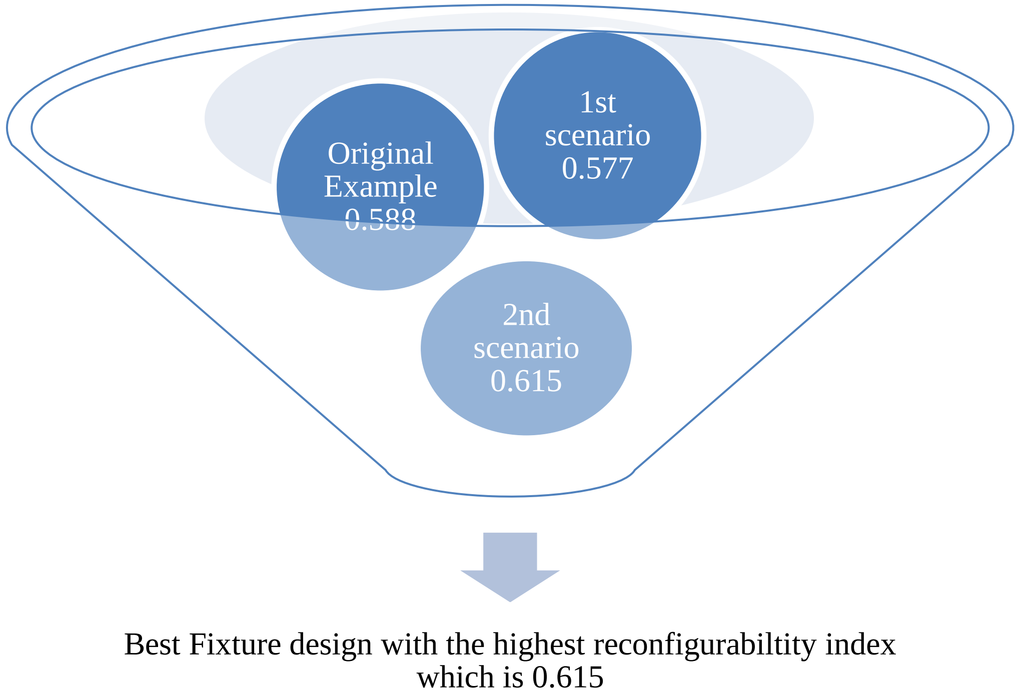


Figure 4.14: The best fixture design reconfigurability

The second design configuration for assembly fixture is the most appropriate design because it designed to produce the same number of product variants with less reconfiguration time, cost, effort, and complexity due to the reduction of the number of modules in the assembly fixture. The second-best design configuration is the primary example with 0.588 reconfigurability.

It can be seen that reducing the number of modules and combine two or three modules can help to reduce the reconfiguration time, cost, complexity, and the effort of the reconfiguration. In the end, it is a matter of trade-off between all the characteristics that designers must take into consideration, along with other factors such as the cost of manufacturing a certain fixture design.

4.4 Discussion and Validation - Comparison Between the Original Example and Obtained Results

In the original example, the assessment of reconfigurability financial potential was measured based on two factors: convertibility and reusability of the reconfigurable assembly fixture (Bejlegaard et al., 2018). Bejlegaard et al. (2018) did not measure the fixture scalability, modularity, or customization. The method that he used to evaluate the convertibility was based on the reconfiguration time. Bejlegaard et al. (2018) mentioned that the reduction in time spent changing the fixture between product component variants was sufficient to bring down the time spent on individual changeovers from 45 minutes to only 10 minutes, which could be around 130 hours savings annually.

In this thesis, the method to measure the convertibility is proposed based on the definition of the convertibility which is the ability of reconfigurable assembly fixture to quickly transform the functionality of existing modules and controls to suit new production requirements, that include the conversion of the functionality of modules within a family to meet the variations. The approach to measuring the convertibility was based on using an analogy with the convertibility of a reconfigurable manufacturing system. Since a fixture performs significant tasks such as locating, supporting and clamping, and a fixture is a product and a system depending on complexity, approaches to assess the reconfigurability of a manufacturing system could be used to assess the configurability of fixtures. Wang et al. (2016) measured the convertibility depends on the number of modules that need to be adjusted.

Similarly, in measuring the convertibility of the reconfigurable assembly fixtures, the main parameters that affect the convertibility of the reconfigurable assembly fixtures are the number of modules that need to be adjusted.

On the other hand, Erdem (2017) provided a different method to evaluate convertibility. He used binary indices for convertibility, which means the convertibility was assessed to be either 0 or 1. This method did not actually measure the convertibility because the indicated index would refer to that the fixture is convertible when the index as 1 or not convertible when the index is 0.

4.5 Conclusion

In this chapter, the two redesign recommendations for the welding tack fixture are applied. The reconfigurability for the original fixture design and the two suggested design configurations are measured. The results show that the second redesign is the best design for the assembly fixture because it has the highest index of reconfigurability index which is 0.615. The reconfigurability of the second redesign scenario is 5% higher than the reconfigurability of the original fixture design and 7% than the reconfigurability of the first redesign recommendation. The recommendations in the second redesign scenario improve the reconfigurability of the fixture for reusability and less cost because reducing the number of modules and combining two or three modules can help to reduce the reconfiguration time, cost, complexity, and the reconfiguration effort.

In conclusion of this chapter, the best design configuration means the highest index of reconfigurability index of the assembly fixture, which is designed to be used with many product variants but with less cost, reconfiguration time, and complexity.

CHAPTER 5

CONCLUSIONS AND RECOMMENDATIONS

5.1 Research Significance

This research has introduced a new integrated method to assess the reconfigurability of the assembly fixtures. This assessment method combined the four core reconfigurability characteristics: scalability, convertibility, modularity, and flexibility.

The research outcome and results have industrial significance and benefits. The main significant point in this research is to help in the design stage of the assembly fixture by comparing different configurations for the assembly fixture to select the most appropriate one to meet the anticipated product variations. This proves the research thesis hypothesis.

In addition, suggesting some changes for the assembly fixture design and configuration is essential to minimize the number of fixtures to be produced when the new part component/ variant is introduced. These recommendations also help to shorten the reconfiguration time and reduce complexity and cost. Doing so also reduces the manufacturing costs and time because these assembly fixtures could be reused many times for different variants and processes.

5.2 Novelty

This research developed an integrated method to assess the reconfigurability of assembly fixtures. The assessment is based on four core reconfigurability characteristics: scalability, modularity, convertibility, and customized flexibility. A clear definition of the scalability of the reconfigurable assembly fixtures was developed. In addition, the developed measurements of the scalability, flexibility, and convertibility based on reconfigurability time, and the number of components was not covered in the literature. Moreover, the combination of quantitative indices for the four characteristics in an integrated mathematical model and using the radar method to combine them into a reconfigurability index for a reconfigurable assembly fixture is new and was not introduced before.

5.3 Conclusions

The designers of new configurations of the fixture can offer a variety of feasible reconfiguration schemes based on different emphases when considering numerous factors such as the reconfiguration time, and reconfiguration difficulty and cost.

The developed integrated reconfigurability index of assembly fixtures at the early design stages is significant to identify and help select the most reconfiguration efficient fixture design configuration. In addition, making some fixture design recommendations help to shorten the fixture reconfiguration time and reduce its complexity and cost. The fixture designer would make the final decision based on additional factors such as the fixture manufacturing cost and reconfiguration time. Efficient fixtures reconfiguration helps to reduce the manufacturing costs and time because these assembly fixtures could be reused many times for different variants and processes.

5.4 Recommendations for Future Work

While research in this thesis focused on large size fixtures, the developed mathematical models and the assessment methodology apply equally to small and medium size fixtures.

Future work may include applying this approach to industrial assembly fixtures with more complex configurations and different sizes, including robots end-effectors, to test further and verify the developed method. Cost analysis can also be carried out to supplement the comparison between designs based on reconfigurability. In addition, future work may relax the assumption that the weight of various characteristics (customized flexibility, scalability, modularity, and convertibility) are equal by assigning a designer assigned relative weight between 0 and 1 to each reconfiguration characteristics before calculating the integrated reconfigurability index.

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VITA AUCTORIS

NAME:	Diana Naser
PLACE OF BIRTH:	Baghdad, Iraq
YEAR OF BIRTH:	1991
EDUCATION:	University of Technology, 2 years in Mechanical Engineering, Baghdad, Iraq, 2010
	University of Windsor, B.Sc. in Mechanical Engineering, Windsor, ON, 2017
	University of Windsor, M.Sc. in Industrial Engineering, Windsor, ON, 2019