CHALMERS

Application of a Design Method for Manufacture and Assembly

Flexible Assembly Methods and their Evaluation for the Construction of Bridges

Master of Science Thesis in the Master's Programme Design and Construction Project Management

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Department of Civil and Environmental Engineering
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Demonstration of easy assembly

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ABSTRACT

The core of this thesis work is formulated by tasks of identification, rationalization and evaluation of technical solutions, bridge concepts and assembly methods being used in other sectors. The concept of Design for Manufacturing and Assembly (DFMA) will be applied for the evaluation of these flexible assembly techniques and bridge concepts. In order for this to happen, this paper primarily lays a theoretical background of the concept of DFMA and criteria that need to be fulfilled in the successful implementation of the system. These DFMA requirements are further processed together with parameters that are bridge specific for realization of a more consolidated set of general DFMA criteria that are adaptive to the construction and/or installation of bridges. The general DFMA criteria are then studied from a manufacturing and assembly perspective which yields characteristics that belong to each block. By tracing the properties of the said manufacturing and assembly characteristics, goals set by project PANTURA are expressed in terms of their respective manufacturing and assembly characteristics. The criteria prescribed under each PANTURA indicators are then utilized as basis for qualitative evaluation of assembly methods and bridge technical concepts, presentation of which form part of the research work. Evaluation of each assembly techniques and bridge concepts has been done according to the extent to which they fulfil the PANTURA goals.

During the course of the work certain difficulties that are inherent in the nature of the construction industry and context of the work are also traced and remarks are made on them. Further studies on this topic can be conducted by limiting the subject according to parties involved in the overall construction process and/or work methodologies that are followed on-site.

Key words: design decision support tools, design methods, bridge construction, industrial thinking, Design for Manufacturing and Assembly, criteria, knowledge transfer, evaluation, PANTURA indicators

Applicering av Design Metod för Tillverkning och Montering
Flexibla monteringsmetoder och deras utvärdering för brobyggande
Examensarbete inom Design and Construction Project Management
MICHEL KALYUN & TEZERA WODAJO
Institutionen för bygg- och miljöteknik
Avdelningen för Construction Management
Chalmers tekniska högskola

SAMMANFATTNING

Kärnan av detta examensarbete består utav uppgiftsidentifiering, rationalisering och utvärdering av tekniska koncept, brokoncept och monteringsmetoder brukade i andra industrier. Konceptet Design for Manufacturing and Assembly (DFMA) kommer att tillämpas för utvärdering av dessa flexibla monteringstekniker och brokoncept. För att göra detta genomförbart, kommer det i första hand ett utlägg av den teoretiska bakgrunden för begreppet DFMA att genomföras och de kriterier som krävs för en lyckad applicering av systemet. Dessa kriterier kommer att tillsammans med parametrar specifika för brokonstruktion att bearbetas och genomgå en förverkligandet av en ny uppsättning generella DFMA kriterier som är anpassade till byggande och/eller uppförande av broar. De generella DFMA kriterierna är därefter studerade ur tillverkning- och monteringsaspekter för att i enlighet med deras egenskaper delas upp i de två perspektiven. Genom att spåra egenskaperna för tillverkning- och monteringskaraktärer, kan de vidare användas vid tilldelning för de indikatorer som projektet PANTURA har satt upp i enlighet med deras uppsatta mål. De kriterier som föreskrivs under varje PANTURA indikator används sedan som underlag för kvalitativ utvärdering av monteringsmetoder och brotekniska koncept, en presentation som är del av detta arbete. Utvärderingen av varje monteringsteknik och brokoncept har gjorts i enlighet med den utsträckning som uppfyller PANTURA målen.

Under arbetets gång har vissa svårigheter naturliga till byggindustrin och omfattningen av arbetet uppdagats, vidare uppmärksammats och kommenterats. Fortsatta studier inom temat kan utföras genom att begränsa ämnet efter parter involverade i den övergripande byggprocessen och/eller de arbetsmetoder som följs på byggarbetsplatserna.

Nyckelord: beslutsverktyg för konstruktioner, design metoder, brokonstruktioner, industriellt tänkande, Design for Manufacturing and Assembly, montering, kriterier, kunskapsöverföring, utvärdering, PANTURA indikatorer

Contents

Preface

This master's project is conducted in partial fulfilment of the requirements for a master's degree in Design and Construction Project Management and was carried out in the department of Structural Engineering at Chalmers University of Technology, Sweden, in collaboration with NCC Teknik, Sweden. The period of the research lasted from January 2012 until July 2012.

Primarily, we would like to thank our supervisors Mohammad Al-Emrani (Associate professor) and Valbona Mara (Ph.D. student) at Chalmers University of Technology, for their valuable inspiration and support during the course of the research. We also would like to forward our gratitude to Christina Claesson-Jonsson, Alexandre Mathern and Tobias Larsson from NCC Teknik for all the help and encouragement they provided for the accomplishment of this thesis work. We are grateful for the feedback and comments we got from our opponent group, Davis Barbars and Thomas Odams.

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Göteborg, July 2012

Michel Kalyun & Tezera Wodajo

Table of abbreviations

CE	Concurrent Engineering
AMT	Advanced Manufacturing Technology
DFMA	Design for Manufacture and Assembly
DFX	Design for X
DFA	Design for Assembly
DFM	Design for Manufacture
FRP	Fibre Reinforced Polymer
NPD	New Product Development

1 Introduction

Traditional construction process is often criticised for being inefficient, unsafe and environmentally unfriendly (Sebastian, 2011). The underlying reason for this can be the characteristic of construction projects to involve a non-continuous process and its project based nature. Consequently, this makes standardization and development of efficient and sustainable resources utilization difficult. Civil infrastructure projects are of a key importance in the context of urban environment. According to Sebastian (2011) these projects are large-scaled and long-term with a characteristic of involving major investment, long preparation and construction time, and usage of significant amount of resources. Due to the importance and public value of civil infrastructure facilities, there will always be continuous demand for new and rehabilitation of existing utilities in a modern society. If carrying out urban infrastructure projects is inevitable (Sebastian, 2011), assessment of their construction to bring the required efficiency is vital. There is an overwhelming utilization of resources and waste generation in the course of construction and maintenance of large-scale construction projects, the consequence of which is an overall impact on the socioeconomic setting of the urban environment. During the construction and maintenance of major infrastructure projects, for example bridges, there are a wide range of factors that will be beleaguered. These factors are used as success criteria/indicators in European Project PANTURA, to measure the performance of projects for their supportive measures in promoting these socioeconomic goals. Few of these socioeconomic factors are environmental wellbeing, workers' safety, users' comfort and welfare, mobility, total life cycle cost, and waste generation.

Productivity in construction is directly related to efficient use of resources. There are different ways by which a construction process can be efficient. One of these ways is working towards the simplification of assembly processes on-site. Thus careful investigation and problem identification in assembly methods and processes is at the heart of bringing efficiency and productivity.

This research seeks to investigate existing innovative assembly techniques and methods that are being used in the construction and other industries within the domain of Design for Manufacture and Assembly and PANTURA goals in order to bring the said achievements to the construction sector focusing on bridges.

1.1 PANTURA project

This master thesis work is part of the European research project named PANTURA. The project's aim is to obtain low-disturbance sustainable urban constructions, with a focus on bridge construction. The background of the project arises from an urgent need to assess existing bridges which are in danger of obsoleteness or have structural deficiency. Therefore, part of the PANTURA aim is to deliver methods, tools and techniques for the cause of repairing and constructing new bridges. As stated in PANTURA (2011), the main goals of the project are to devise and introduce new methods for the construction, maintenance, repair and renovation processes of bridges. The construction process has to be done in the most effective and efficient way, within a defined project duration. Sustainable use of resources with zero disturbances for the urban environment is also an important entity of the goals.

The research work in the EU PANTURA project is spread out and divided among a consortium of different organizations, authorities, industries, universities, etc. From the aim, several different objectives are formulated, and different work packages are compiled from the objectives. This thesis work is initiated in a view to contribute to the fourth work package, named: "Flexible construction techniques for new bridges"

1.2 Concurrent Engineering, Lean Manufacturing and Design decision support tools

Nearly all construction projects involve direct construction work as a major part of the process, and this accounts for a great deal of the cost and time engaged in a construction project. This calls out for a need to learn from best experiences and knowledge sharing across industries so as to attain similar results achieved in other industries. Yet, for a general manufacturing, an estimated 70% of a production cost is determined at the design phase (Dewhurst, 2011, Wu and O'Grady, 1999). Thus putting more attention on the realization of manufacturing issues early in the process is a proven strategy to reduce cost and bring the aforementioned efficiency. Promoting synergy among various industry professionals and consideration of potential cost and time incurring issues early during design stages forms a part of the solution which addresses problems that cry out for remedies.

The prediction and consideration of a product's downstream behaviour early in the design stage is a typical characteristic of Concurrent Engineering. A product development process that makes use of the Concurrent Engineering approach is characterized by the cooperative design, production, distribution, and support divisions throughout the life of a product (Wu and O'Grady, 1999). In this regard, Concurrent Engineering can be considered as a product development process performed under the influence of varied types and enormous number of criteria. Unlike sequential engineering, more diverse design objectives are exercised when working with Concurrent Engineering (Wu and O'Grady, 1999). Taking into account the varied design objectives and constraints appear to be a bugbear for practitioners that are involved in industrial design tasks. The management of these various constraints and the different design objectives in Concurrent Engineering has led to many implementation methods in Concurrent Engineering (Wu and O'Grady, 1999, Mendoza et al., 2003).

Each product development phase has its own distinguished attributes resulting in a different level of impact in the overall project lifecycle. Thus it is imperative in the first instance, to distinguish which part of the product lifecycle requires attention in order to achieve the best outcome of efforts engaged to minimize overall manufacturing cost and shortening the time to market a product. In the overall sense of waste elimination and value generation during a product development process, the concept of lean manufacturing is one of a kind which plays an important role in the manufacturing industry. Lean manufacturing as defined by (Dewhurst, 2010), is a cost-reduction and efficiency philosophy that has an unwavering focus on eliminating waste. Lean manufacturing, one among certain valuable techniques, strives to work for improved quality, lower cost and shorter product cycles through a relentless effort to minimize waste and promote product value adding activities in the production process. What is not commonly seen in traditional Lean Manufacturing approaches is an equally vigorous emphasis on the product itself (Dewhurst, 2010). Lean manufacturing initiatives rather enable engineers to excel at eliminating waste during the actual assembly process. This limits the focus of lean concept mainly on the actual product assembly process. The mere focus on assembly phase of a product is thus a pitfall in lean manufacturing as it does not account the causal relationship between part design and production efficiency (Dewhurst, 2011). What product developers have to realize is the potential cost and time that can be saved by engaging the application of certain design decision support tools. These make us able to design a product for efficient manufacture and assembly. The prediction of future manufacture and assembly issues early in the design process actually ensures a potential result of eliminating waste before the product actually reaches the production line (Dewhurst, 2011). As it is explained earlier in this section, different scholars have referred to Concurrent Engineering as an approach which puts forward a need of rigorous efforts to consider every possible downstream impact of earlier design decisions and getting involved multiple design objectives as determinants of a design, manufacture and production approach. The relatively narrow viewpoint of a Lean manufacturing is also manifested as a pitfall for it hinders the prediction and consideration of downstream issues rather in earlier product lifecycle phases. In an effort to facilitate these important tasks, manufacturing companies and researchers have developed certain design decision support tools collectively referred to as Design for X (DFX) (Herrmann et al., 2004). Accordingly, any specific design decision support tool, such as Design for Assembly, Design for Manufacture, Design for Environment, Design for Disassembly, Design for Service, or Design for Six Sigma are subsets of the DFX umbrella (see Figure 1).

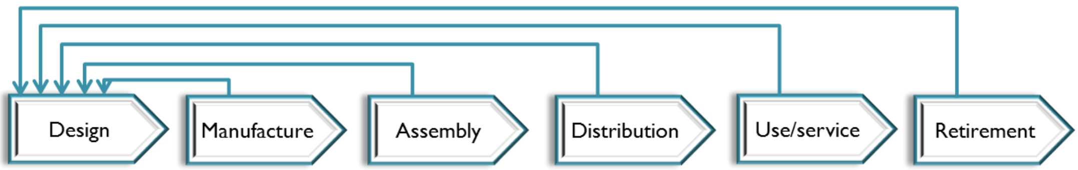

Figure 1-1 Design for different requirements, DFX (modified from Eskilander 2001)

These design decision support tools are regarded as yielding considerable importance in the relentless manufacturing and assembly processes of a product lifecycle. This is mainly because of their respective focus on the design objective they are devised for. For instance a tool which is developed for the design of manufacturing deals with designing the parts based on material choice and other criteria for easy manufacturing. Similarly, a tool devised for designing the assembly of the parts deals mainly with the design of the assembly operation. This as a consequence leads to additional benefits in increased quality, reliability, shorter manufacturing time and overall efficiency in the assembly process, which is responsible for more than 50% of total manufacturing cost and 40% to 60% of total production time (Wu and O'Grady, 1999).

Among the various available design tools is the Design for Manufacture and Assembly (DFMA), a tool that helped manufacturers to create world-class products with improved quality, lower cost, and shorter design cycles (Dewhurst, 2010), by systematically rationalizing product development and improving easiness of a product’s development from its part manufacturing down to the assembly stages (Lahtinen, 2011). Thus DFMA facilitates efficiency of a production system by providing at hand knowledge about upcoming product manufacturing and assembly issues and enables practitioners and product developers to map, evaluate and rationalize how the actual manufacturing and assembly process would look like.

1.3 Background

As being widely implemented, Lean manufacturing, Concurrent Engineering and other design and production philosophies have recently been used to support remedies for pitfalls of cost overrun, time slippages and waste generation in the production of goods. Efforts of Lean process or any other systems of production are primarily driven from an initiative to reduce production cost and making an impact on profitability. Traditionally, attempts to saving costs have been done through job cuts or improving operational efficiency. Yet, continual efforts have to be employed to understand, control, and reduce costs from the early stages of product development (Dewhurst, 2010).

Allocation of enough time and effort to the understanding of the design of a product is a fundamental factor for the ultimate success of the Lean philosophy (Dewhurst, 2010). Careful and informed design decisions have to be made earlier in the product development phases so as to tackle problems of re-work and avoid potential design faults at late stages of the lifecycle. Early awareness of the consequences of design decisions can be triggered by the use of design decision support tools like DFMA. These tools help in the realization of what additional attributes can be achieved by taking the lean initiatives to the design stage instead of a mere action on the direct manufacturing process.

This thesis is initiated due to a lack of proper understanding of the potential applications of DFMA in the construction and assembly of bridges. The short comings attributed to Lean initiatives will be sought to be mitigated by a systematic use of Concurrent Engineering and DFMA principles.

1.4 Purpose and objectives

Achievement of the said high degree of effectiveness not only involves a mere cost reduction and/or on time accomplishment, but also criteria such as, minimization of issues like human work, traffic disruption and social costs. The target of elevating these efficiencies in bridge construction and assembly can be met by flexible and easy assembly techniques, as these may allow turning construction sites into high technological areas with clean work environments, calm and safer conditions.

In this thesis work technical solutions and manufacturing and assembly design principles that are used in various sectors will be researched, identified, rationalized and evaluated for their potential use in the construction and/or assembly of bridges. This in turn creates easy and efficient assembly processes on-site thereby achieving efficiency in terms of cost, time and creating better job environment for workers involved in the assembly. Before the introduction of new assembly techniques, important DFMA criteria in other industries will be identified. The aggregate of these criteria will form a filtered framework of manufacturing and assembly characteristics into which the PANTURA indicators will be translated. The identified techniques of assembly and technical concepts will then be evaluated, for their potential use in the construction sector, in accordance with the DFMA criteria and PANTURA indicators.

1.5 Method

In an effort to approach the subject matter defined in the section earlier and meet the purpose for which project PANTURA stands, a database search and review of relevant articles was conducted, in order to obtain the required level of knowledge about DFMA systems and their contemporary use in different industries. The basic principles underpinned together with the merits and demerits of DFMA systems were studied from relevant literature, webpages, manuals and company brochures. When there is a puzzle and knowledge gap due to lack of adequate information, few structured interviews were conducted with industry practitioners.

A series of e-mails were also sent to various companies, in a view to obtain additional information, drawings and reading materials to further strengthen the knowledge sought about their assembly techniques and processes. In cases where certain technical information is required, and qualitative interviews are difficult to give precise information, further study of reading materials on the referenced assembly techniques are done. The interviews together with the study of available drawings and work process descriptions sealed the crack of this knowledge lack.

The subject matter is approached in a systematic way, by first studying the existing knowledge about DFMA, its benefits and drawbacks and then pointing out important criteria to be fulfilled when working under DFMA systems. Another set of criteria are also formulated based on critical bottle necks encountered in the construction of bridges. A combination of these two sets of criteria form the framework to which the PANTURA indicators will be translated. At a later phase of the research, the reviewed new assembly techniques will be evaluated for their performance in meeting the combination of the criteria set. Examples and demonstrations, wherever possible, are also used for easy understanding of the methods and techniques of assembly that are being discussed. In summary the following parts are to be treated in the course of this work:

- An overview of contemporary knowledge about DFMA systems, their benefits and downsides
- Pointing out important criteria that are required to be fulfilled when working with DFMA systems
- Formulation of criteria for the assembly/construction of bridges and bridge parts depending on bottle necks in the construction and assembly of bridges and bridge parts according to PANTURA goals
- A systematic translation of PANTURA indicators into the framework of DFMA criteria
- A review of industrialized and smart techniques of assembly developed from other disciplines and new technical concepts for the assembly of bridges
- Evaluation of the reviewed new assembly techniques in accordance with DFMA criteria and PANTURA goals for their potential use in bridges assembly

1.6 Scope and limitations

The scope of this work is defined to:

- The use of DFMA principles for the assembly of bridge elements.
- The study of Lean and Concurrent Engineering philosophies through the spectacle of DFMA and how pitfalls in the respective concepts can be mitigated by the use of DFMA
- Presentation of the technical concepts and assessed assembly techniques as they are being used in their respective industries. They will not undergo any structural assessment, analysis or load bearing capacity determination for adoption

- Evaluation of the assembly methods from a holistic viewpoint of the DFMA criteria which will be categorized into PANTURA indicators. The evaluation will not be performed in a way of criteria-evaluation loop, where criteria are reset continuously and re-evaluation follows.
- Introduction of new knowledge from other industries regarding DFMA into the assembly phase of bridges and forwarding recommendations for further design work based on the criteria set for evaluation
- Consideration of the entire project cycle as DFMA covers greater part of a project, from the design to the assembly, and it is difficult to focus on a single project phase while working with DFMA.

Furthermore, in this research, whenever the reader encounters an expression “bridge construction”, there should be a common understanding that the work situation under consideration is the installation, assembly and fastening of bridge elements and parts.

2 The Concept of Design for Manufacturing and Assembly (DFMA)

Before undertaking any further study for the applicability of DFMA systems in the construction industry, understanding of terminologies and realization of the system from a broader perspective is crucial. A closer look at different industries in order to grasp genuine understanding of the processes associated with DFMA systems, can ease the knowledge transfer and applicability to other industries of interest.

In this chapter, varied perspectives of defining DFMA systems are presented, followed by the needs to use the system in the construction industry alongside the benefits and challenges associated in the process of customizing the system and knowledge transfer.

2.1 Defining DFMA

Understanding and defining the meaning of DFMA as a system requires prior knowledge of the words for which DFMA stands for. Cambridge advanced learners' dictionary gives a meaning of the word "*Design*" as

> *"A drawing or set of drawings showing how a building or product is to be made and how it will work and look"*
>
> *"The art of making plans or drawings for something" or*
>
> *"The way in which something is planned and made"*

The word "*Manufacture*" is used to describe the business of producing goods in large numbers, usually in a factory using machines. According to the dictionary, the word "*Assembly*" is used to describe the process of putting parts of a machine or structure together or is alternatively used to refer to the structure produced by this process of putting the parts together.

Based on the meanings of each word described above, a preliminary definition of DFMA can be drawn from an industry point of view as:

> *A system by which ways of efficient manufacture and configuration of smaller parts are planned and made possible for their use in making bigger structures by putting them all together.*

When considering DFMA, it is crucial to separately consider the design for the manufacturing process of the assembly parts and the actual assembly process used for the creation of the final product. A manufacturing process makes use of available resources to produce smaller parts which are assembled to yield the final output. Hence the term manufacturing is associated with the process of machining, moulding and producing the collection of parts that will form the final product after assembly (Boothroyd et al., 2004). The outcomes of manufacturing process, thus, are parts that have the required technical capabilities, surface finish, overall shape and tolerances. Whereas, assembly, on the other hand, refers to the addition or joining of the parts that are produced during manufacturing, we can assume here also not to regard minor joining tasks during manufacturing as assembly (Boothroyd et al., 2004). In this sense, an assembly process of a production system is required to meet certain standards that are attributed to lead times, yield rate and production rate (Giachetti, 1999). Schematic representation of the application of DFMA in product developments is presented in Figure 2-1.

DFX tools is a collective designation attributed to any of a variety of design considerations occurring throughout a product development process, such as manufacturing, assembly, quality, production, and environmental impact (Herrmann et al., 2004). Expressively, when a DFX tool is used for the design of manufacturing and/or assembly it thus inherits a designation of Design for Manufacturing (DFM) and Design for Assembly (DFA) respectively. DFM and DFA constitute two of the most common and popular DFX tools as they allow better assessment of the downstream life cycle impacts of design choices that are made upstream (Herrmann et al., 2004). DFX tools serve this purpose by availing knowledge of manufacturing, assembly, quality, production, and environmental criteria so that designers can consider possible remedy for potential problems.

Design for Manufacturing and Assembly (DFMA) is a system which is built from building blocks that are born from a separate treatment of the manufacturing process and production system of a product lifecycle. DFM and DFA are the two elements that allocate increased percentage of time spent on the conceptual design phase of a product development (Stone et al., 2004). These two blocks of DFMA are important milestones of a certain product development process, as DFM is used in the earlier realization of technical criteria that need to be fulfilled by successful making of the assembly parts (Giachetti, 1999, Stone et al., 2004, Martin, 2002, Dewhurst, 2010). In other words, DFM allows designers and product developers to acquire early knowledge of the technical and/or managerial specifications of parts, thereby laying a fertile ground for devising methods of manufacturing that come in accordance with the specifications set. On the other hand, satisfying the production standards that are attributed to lead times, yield rate and production rate is made possible by the application of DFA systems to design and develop products with fewer parts and promote easier assembly in the aspect of time and work (Giachetti, 1999, Stone et al., 2004, Martin, 2002, Dewhurst, 2010).

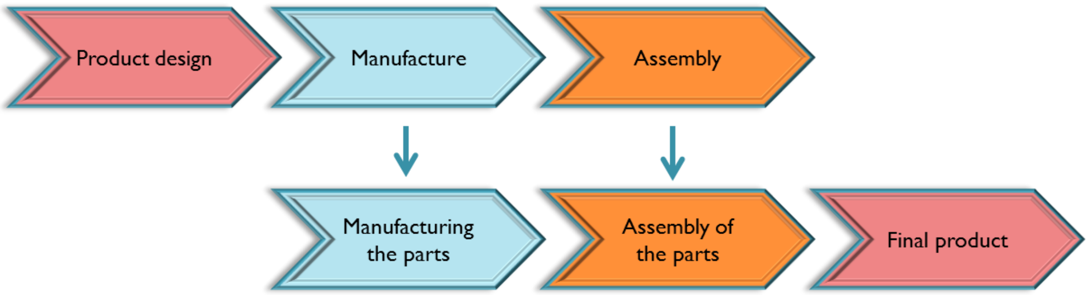

Figure 2-1 Elements of DFMA

The underlying concept of DFM dates back to late 1780s, when LeBlanc, a Frenchman, devised methods for the use of interchangeable parts in the production of muskets (Martin, 2002). The development of design guidelines for easy 'producibility' had started as early as 1960s (Boothroyd, 1994). This has paved the way for the application of DFMA systems in an organized and disciplined manner. However, it is mentioned in (Boothroyd, 1994) that, in earlier times when guidelines were devised for efficient designs, the emphasis was mainly on the 'manufacture' block of a product development cycle. Lack of enough attention for the assembly process prevents integrated implementation of the two equally-important constituents of DFMA. It is since 1980 that analysis tools have been introduced resulting in conceivable products that are easy to manufacture and assemble (Boothroyd, 1994). One of these established tools is DFMA, which has been helping product developers in efforts to improve quality, lower cost, and shorten product cycles (Dewhurst, 2010).

Principles of DFM are used in integration among each other so as to avoid potential rework and cost appreciation pitfalls. These principles are presented in (Martin, 2002) (see Figure 3) and are elaborated as follows:

- Set product specifications in accordance with user needs and requirements
- Perform market forecasts, project sales volumes, determine unit price and demand
- Structuring a customized product development process. This includes planning the conceptualization, definition, prototyping and testing phases
- Performing the component/parts design, subassembly design, and assembly analysis
- Reviewing quality requirements for their proximity to user requirements
- Material selection, process selection and suitability check
- Undertake cost vs. benefit/economic analysis
- Feasibility study for the design performed and re-design if required
- Production and commercialization

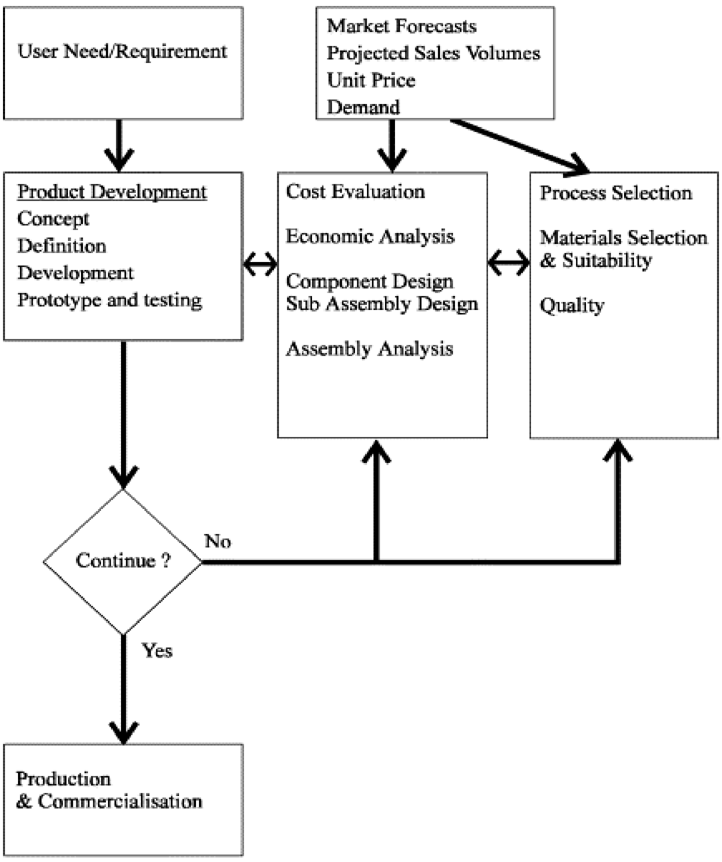

Figure 2-2 Schematic representation of a typical DFM flowchart (Martin, 2002)

Traditionally, manufacturing is assumed to begin with a preliminary decision making on material, manufacturing process and vendor selection (Giachetti, 1999). At the very beginning of a product development process, little is known about the end product features and intricate problems associated. It is at this early phase of a product development that suitable materials and manufacturing processes are chosen on the criteria set based on available knowledge about preliminary product profile requirements, financial considerations, quality, design support and engineering capabilities (Giachetti, 1999). As it is also shown in Figure 2-2, Design for Manufacture provides guidance in the selection of materials and processes and generates piece part and tooling cost estimates at any stage of product design. It encourages the use of suitable materials and manufacturing design processes by providing designers with the required viable information for comparison with more feasible design alternatives and material selections (Boothroyd Dewhurst Inc, 2012).

The objective of DFA is to obtain a design that guarantees efficient and cost effective assembly operations by taking assembly operations and related support activities into account during the design process (Wu and O'Grady, 1999)**.** DFA is mainly concerned with the assembly process of parts that are products of the DFM block. DFM, being a critical component of the DFMA process, complements DFA by providing manufacturing knowledge into the cost reduction analysis of Design for Assembly (Boothroyd Dewhurst Inc, 2012).

An integrated application of DFM and DFA eliminates the sequential nature of traditional product development processes and brings a design and manufacturing procedure which is rather iterative as can be seen in Figure 2-3. The scheme below shows how DFMA works iteratively in new product developments. At each stage of the process performance measures are used to indicate the accomplishment of specific design objectives, facilitating the production of goods that have the desired manufacturing and assembly features.

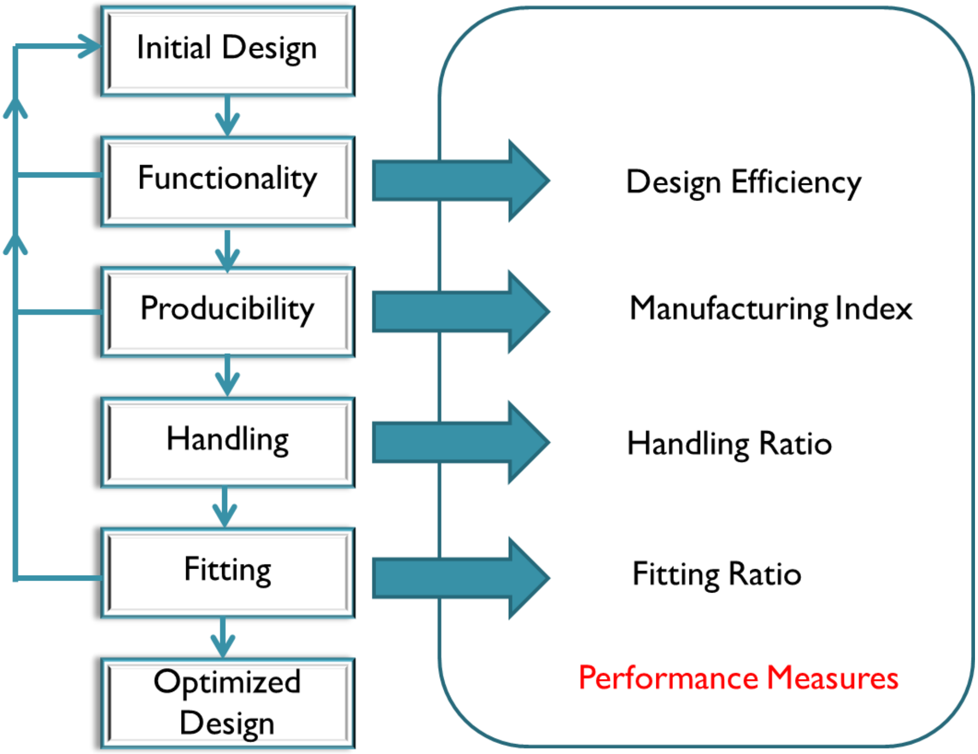

Figure 2-3: DFMA Procedure (Ranky, 1999)

Design for Manufacture coupled with Design for Assembly formulates a system of DFMA tools which give engineers an early cost profile of product designs (Boothroyd Dewhurst Inc, 2012), thereby enabling them to take considerations of how the product will be made, shipped, installed, used, serviced, and retired or recycled during design phases of a product development (Herrmann et al., 2004). In general, DFMA provides a fertile ground for upstream planning and decision making which determines downstream life cycle issues. This not only reduces the number of redesign iterations, the time-to-market, and the development and manufacturing costs but also improves customer's experience (Herrmann et al., 2004).

2.2 Why DFMA – benefits and challenges

Generally Concurrent Engineering and the concept of Lean, as they were explained in the earlier chapter, can be considered as production philosophies, which ultimately focus on making a certain manufacturing/production system efficient, bringing the intended cost-reduction, achieving improved quality, and shortening design cycles. The concept of Lean gives greater (if not full) attention to the manufacturing process of a certain production system, striving to eliminate activities on the production line which do not have a direct influence over the value creation of the final output. What we do not see traditionally from Lean Manufacturing initiatives is an equally vigorous emphasis on the product itself (Dewhurst, 2010). One advantage of implementing the Lean process, as explained in (Dewhurst, 2010), is reduction of production cost and making an impact on profitability. Traditionally, strategies to achieve cost reduction have been done through mere treatment of the issue from the perspective of operational efficiency and spending cuts. Especially in traditional design approaches, enough attention has not been paid for the relationship between early design decisions and final product cost. Due to its characteristics of revealing product cost at later stages and the sequential nature of activities, traditional approaches of product design (see Figure 2-4) impede utilization of the advantages of early product knowledge and design decisions for the erection of beneficial downstream functions in the lifecycle (Martin, 2002).

Figure 2-4 Sequential design approach

Apart from its adverse effect by creating potentially poor design, the sequential design approach also cast a shadow on product cost. Recent researches made on traditional design methods have revealed that the direct cost consumed by design of a product is approximately only 10% of the budget (Martin, 2002), despite the fact that 70% of the product cost is determined during the design phase (Dewhurst, 2010). It is important here to note that cost of materials and manufacturing processes accounts for 50% to 80% of total product budget. Due to lower budget percentage allotted for design phase, design professionals, manufacturing engineers and production managers are provided with minimal playground to influence downstream lifecycle functions. This severely hinders attempts to reduce overall product costs in the sequential design approach (Martin, 2002).

Before undertaking any trial to devise strategies of cutting costs and promote efficiency, it is imperative to fully understand the potential factors and elements of a work process which causes cost implications. Cost implications and their sources need to be fully understood to effectively control and ultimately reduce them as the overall product development evolves. Fundamental to the ultimate success of Lean is an unwavering focus on eliminating waste and investment of time to understand the design of the product for which an attempt to create a Lean process is made

(Dewhurst, 2010). During an early effort to grasp a deeper knowledge of the output beginning from the product conceptualization and design phase, factors that have an impact in the creation of efficient production systems will also be realized simultaneously. This attribute, for example, can be manifested through the current wide acceptance of Lean Manufacturing as one remedy to overcome problems of cost escalation in a production process (Dewhurst, 2010). But cost escalation is only one example of the many failures that are encountered in the overall product lifecycle which involves a web of processes with associated drawbacks. In a situation where there was scarcity of systems of recognizing and remedying these drawbacks, Concurrent Engineering and DFX tools came into existence and serve the purpose of bridging this gap.

2.2.1 Benefits

In order to fully understand the said impact of design decisions on late product features, the use of tools such as DFMA is of great importance. As it was explained in earlier sections, DFMA works in proximity to the concept of Lean, as it makes use of tools and brings about benefits comprehended in lean philosophies. For example waste generating activities or activities that do not directly add a value to the production process do not support the concept of lean production. Thus, they need to be removed from a certain assembly process. Beyond a mere concern on eliminating non-value adding processes, undertaking analyses of manufacturing and assembly upstream in conceptual design phases facilitates the saving of large amount of cost and time of production (Herrmann et al., 2004, Boothroyd, 1994, Boothroyd Dewhurst Inc, 2012). Furthermore, DFMA can contain a wide variety of recommendations, checklists and guidelines, all for contributing to easy manufacture and assembly, but also testability, maintenance and serviceability. These in turn will impose a positive impact on worker environment and bring possible achievements in long term sustainable developments (Lahtinen, 2011).

What difference does a design method bring? In 1990 a worldwide study was made on automobile manufacturing companies (Boothroyd, 1994). At the time, Japan had the most productive automobile manufacturing plants. The study attempted to explain the variations of productivity and extent of automation implemented in the various plants. Results of the study showed that automation could only account one third of the total difference in productivity between plants. The least automated Japanese plant, which had a 34% level of assembly automation, happened to be the most efficient plant in the world. Still the plant had one-half of the human work effort compared with an equivalent European plant. Despite its being the most automated plant with an automated assembly level of 48%, the European plant was identified to involve significantly intensive manual assembly than mere automation. This reveals the fact that efficiency in assembly has a meaning much more beyond automating assembly processes. Furthermore, a conclusion in the study reveals that no matter the operations in the production, a plant cannot be competitive if it has defects in its product designs as product design failures can be hardly compensated by the type of production operations followed in product developments. This puts an equally important demand on quality product designs as efficient production operations. DFMA or other design decision support tools strive to erect a profound product design free of defects causing inefficient productivity.

Even before and after 1990, there have been additional studies conducted on DFMA, about its possible benefits and therefore how early phase planning can induce better results. Typically in project processes, ease of introducing changes in product designs points at its highest level at the start of the project and declines fast during the development process. But it is also crucial to notice the minimum acquired product knowledge at start of the product development process and inclines through the course (see the product development process Figure 2-5) (Herrmann et al., 2004, Boothroyd, 1994, Giachetti, 1999, Boothroyd Dewhurst Inc, 2012, Martin, 2002)

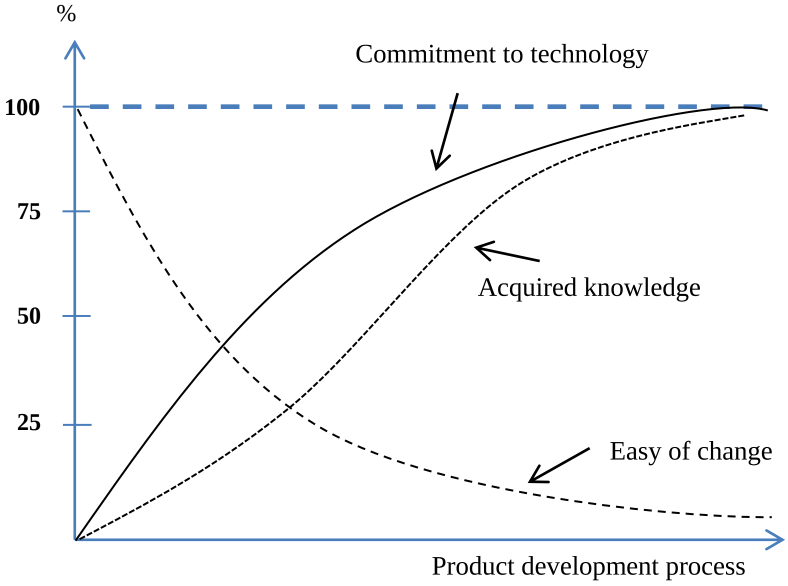

Figure 2-5 Product development process (Lahtinen 2011)

As it is mentioned earlier in this chapter, the DFMA method makes use of an iterative design process (see Figure 2-3) which involves actors from all different levels of a product development. All stakeholders from marketing experts to designers, manufacturing engineers to assembly line workers, and managers to product researchers are given the upper hand to leave their impression on the final output (Herrmann et al., 2004). The possible benefits which can be sought from the implementation of DFMA (Boothroyd Dewhurst Inc, 2012, Dewhurst, 2010, Herrmann et al., 2004, Giachetti, 1999, Mendoza et al., 2003) are summarized and presented as follows:

- Increased time in the conceptual design phase gives shorter time-to-market and development cycles. Also eliminates rework and redesign at later stages.
- Through iterative process, the design team will acquire a better understanding of the product cost. This allows designers to exercise greater control over final cost of the product. 70 % of the cost of a product is determined at the design phase. DFMA with its methods of manufacturing more elegant products with fewer parts can reduce costs.
- The information gathering and detailed analysis in the iterative process enables better decision making.
- During design phase of a product development it can be determined how the product will be made, shipped, installed, used serviced and retired or recycled.
- Improved quality and reliability.
- Establish a rating for the product design in terms of assembly.

- Benchmarking existing products, both internally and/or against competing products.
- Ensures proceedings of design phases by verifying improvements as the design evolves.

2.2.2 Challenges

There is a wide range of companies using DFMA (Fox et al., 2002). Although, with the evident improvements that DFMA delivers into the product development process, it has not been as widely used as it could be (Eskilander, 2001, Mendoza et al., 2003, Tsai, 2012). The question is if this is because of the method itself or the users. Eskilander presents a variant of DFMA that has more guidelines and information on how to design a product and also is simpler to use because of a "common language" as cited. In a trial to overspread and implement the knowledge of DFMA, involvement of multidisciplinary expertise, including designers, production engineers, quality engineers, purchasers, logistics specialists and so on, is crucial. But the involvement of multidisciplinary expertise creates communication and applicability deficits in DFMA. Thus, the medium of instructions and languages used in the system should be easy to understand and communicate with (Herrmann et al., 2004, Eskilander, 2001, Dewhurst, 2010).

The objective of designs is commonly structured to satisfy functional requirements. This has been a common practise by most design engineers (Dewhurst, 2010). It is seldom product developers make earlier consideration of implications that will incur cost and time at later stages. They do not tend to apply revolutionary design philosophies such as DFMA; rather they take it as an extra burden on the existing familiar design task (Eskilander, 2001, Dewhurst, 2010). Not so many design engineers have detailed knowledge of all the major processes defining shape of a product. Consequently, they tend to design for manufacturing processes with which they are familiar (Boothroyd Dewhurst Inc, 2012). In these familiar manufacturing design processes, the cost implication of design decision is given lower priority. The logic behind DFMA will encounter paralysis and the system will become dysfunctional, if it is not practised from the start of a product development process (Eskilander, 2001). There are more underlying difficulties as seen by the designers. First of all, downstream life cycle needs are difficult to predict in such an early phase without multidisciplinary expertise. With a time pressure of delivering design concepts, there is little motivation of adding more methods into the design concept phase that involves other departments in the manufacturing process. Secondly there is a difficulty in communicating and sharing knowledge with today's complex industry structures, where each different department has grown to an own organization. All of the abovementioned issue makes it overwhelmingly difficult to undertake design approaches such as DFMA (Herrmann et al., 2004).

2.3 DFMA: state of the art in various industries

At this point, it is of great importance to look at the ways other industries have approached the principles of DFMA and the results they have achieved. According to the traditional work culture in other industries, during the early stages of development, design engineers are obsessed with satisfying purely functional requirements and are disengaged from the specific cost implications of their earlier decisions (Dewhurst, 2010). Due to its feature of an overly isolated focus on function, traditional design culture however can cause teams to miss their customer target cost.

It is though noted in the contemporary industry work setting that a simultaneous design task for both cost and function generally allows industries to build more performance into products for the same or lower price (Dewhurst, 2010). In this section, advanced manufacturing technologies that allow achievement of the said cost and functionality objectives are presented. Review of the application of DFMA tools in different industries is also an important part of this section to understand the applicability of the principles in the construction context.

2.3.1 DFMA and advanced manufacturing technologies

The current state of industrialized manufacturing and product development involves modern design practices, advanced techniques, technologies and concepts. Primary emphasis is given to processes of production, robotics and other aspects of efficient production. In the sense of involving certain software based technologies, flexible manufacturing systems, as well as intelligent system of planning and control (Boothroyd Dewhurst Inc, 2012), DFMA can be regarded as a tool which facilitates the implementation of Advanced Manufacturing Technology (AMT). AMT, according to (Ding and Zhong, 2011) can be defined as

> “An automated production system of people, machines, and tools for the planning and control of the production process, including the procurement of raw materials, parts, and components, and the shipment and service of finished products”

In the broad perspective of AMT, DFMA seems to satisfy the slot of tooling requirements of a production system, thereby facilitating the iterative efforts of creating flexible manufacturing systems. Facilitated by technological catalysts and systems, the manufacturing industry has undergone considerable alterations from mechanized systems of manufacturing to the present day achievements of AMT, such as Computer-Aided Design (CAD), Computer-Aided Process Planning (CAPP), Computer-Aided Engineering (CAE), Computer-Aided Manufacturing (CAM), Numerical Control (NC), Virtual Prototype (VP), Flexible Manufacturing System (FMS), industrial robot and so on (Ding and Zhong, 2011). Among these technological catalysts, systems and tools one is DFMA. In order to manifest how DFMA tools have made a significant contribution in the modernization of the manufacturing and assembly process, it is enough to see what achievements and benefits have been enjoyed in the manufacturing industry due to the use of DFMA tools.

DFM Concurrent Costing is a software tool used to generate cost estimates of subassemblies thereby providing industries with relatively accurate cost estimates by quickly simulating the use of alternative raw materials, design alterations and various shape-forming processes (Boothroyd Dewhurst Inc, 2012). This feature allows unlimited consideration and testing of alternative materials and process suggestions forwarded by marketing, finance, purchasing and other personnel. One example of such an achievement is pointed out in Martin (2002). According to the article, successful application of DFM brings about a considerable saving in a product manufacturing. Northern Telecom, due to the integration of its manufacturing systems with DFM, enjoys a particular product cost reduction from $410 to $65. Concurrently, the company reduces the number of sub-assemblies required during manufacturing. In this regard, the total number of parts to make the product was reduced from 59 to 32 pieces. In parallel, the time required to assemble the product was reduced from 15 to 5 minutes. Consequently, the annual expected savings were estimated at $3.45 million. Another achievement in the regard of reduced assembly parts and cost efficiency is recorded by Ciba Corning Diagnostics Corporation, a manufacturer of blood gas analysers (Martin, 2002). The successful implementation of DFM for a particular product design, have reduced the overall number of subassembly parts by 48% and the cost by 22%. Based on a wide range survey conducted over thousands of US-based manufacturers, it is also concluded that consideration of DFM criteria early in the product development can result in an overall project cost saving of 10% to 20% (Martin, 2002).

The use of DFM Concurrent Costing has played an important role in revolutionizing the manufacturing industry from a standardized system to an iterative one, where frequent reviews of product cycle can be made so as to achieve the most possible cost efficiency. Moreover, DFM is used in the redesign of existing products for better quality and manufacturability while still adhering to manufacturing cost requirements (Boothroyd Dewhurst Inc, 2012). DFM Concurrent Costing allows redesign of products that meets a certain requirement but not another. For example a product which achieves the required cost efficiency but not a certain functional requirement should be redesigned for the improvement of its pitfalls while maintaining the already met qualities.

The footprints of DFMA tools on the manufacturing industry are in proximity to the ones exercised by the application of AMT. The significant impacts of AMT on manufacturing industry are presented in (Ding and Zhong, 2011). The translations of these impacts, as exercised by DFMA, are presented as follows.

The Upgrade of Product Modeling Method

As noted in Ding and Zhong (2011), modeling is the important activity of product design as manufacturing and assembly instructions together with functions of products are expressed by models or drawings. In the contemporary industry, complex designs can be modeled and analyzed using CAD systems thereby enabling successful tracing of embedded design problems that would not otherwise be identified until the problem comes into physical existence (University of California at Berkeley, 1998). The use of CAD systems has facilitated efficient and swift applications of DFMA tools. Three-dimensional (3D) CAD technology, being one of the most commonly used tools in AMT (Ding and Zhong, 2011), can thus be regarded as a change agent in the evolving processes of modeling methods in DFMA

The Upgrade of Design Test and Evaluation Mode

A great deal of cost and time is incurred in a trial to undergo extensive experimentation and testing of products (University of California at Berkeley, 1998). Building a physical prototype for testing creates unwanted byproducts and generates waste as the experimental products are obsolete after performing the required test. The possibility to simulate and analyze product prospects has made a tremendous transformation from experiential design mode to modern design mode, where unlimited testing of different design methods and shaping techniques are performed virtually. With experimental/traditional design tools, the quality and accuracy of design varies according to the experience of the engineer. Unlike the manual calculation and experimental design methods, digital design tools replace the need for physical prototypes and open the door for simulation, which enables designers to optimize the shape, structure and predict the performance of a product (Ding and Zhong, 2011).

The transformation of Working Mode

Because of AMT the working mode of manufacturing industry has also been revolutionized from manual system of working to digital systems. Nowadays application tools are being used at a significantly higher level to accomplish design tasks (Ding and Zhong, 2011). In a trial to drive efficiency of a manufacturing system, the role of people in the manufacturing and assembly line has changed from pure laborer to operator of digital devices and tools (Ding and Zhong, 2011). The need for change in working mode is manifested by progressing developments in reducing human capital and optimization of production (Miller, 2012). This is accomplished by standardizing processes and deploying robots in work settings thereby achieving the ultimate in repeatability and flexibility (Miller, 2012).

The Transformation of Production Organization Mode

The capacity of technological tools to allow unlimited design parameter changes and consideration of varied types of product functional requirements, has transformed the manufacturing mode from a traditional mass production scenario to a flexible production one. In the flexible production scenario, products are made according to defined user preferences and predicted requirements, as there is no restriction of production technologies and equipment (Ding and Zhong, 2011). With the help of advanced manufacturing technologies, from hardware to software, industries are enjoying a relative flexibility in their production systems in terms of product design, machining technologies and overall organization mode of product development (Ding and Zhong, 2011).

2.3.2 Application of DFMA in different industries

There are enormous companies and organizations that strive to benefit the most out of what can be obtained from integrating DFMA systems in product developments. Alcoa, Boeing, Dell, Electrolux, Ericsson, Kodak, Massey Ferguson, Toyota Microsoft, UTC Power, Westinghouse Electric and Whirlpool are among the companies reporting reductions in product cycle times and total costs, along with better integration of Lean Manufacturing and a renewed focus on "upfront engineering" (Fox et al., 2002, Aerospace Manufacturing and Design, 2011). For the understanding of DFMA applications in these industries, a scant presentation of state of the art is dealt here under.

Aerospace industry

Despite the often made claims of revolutionary designs in the aerospace industry, airframe construction has historically been very evolutionary in nature (Paul et al., 2002). Chris Tsai, DFMA implementation services manager; Boothroyd Dewhurst Inc. has made an explanation to some concerns about the implementation and progress of DFMA systems in the aerospace industry. He pointed out some of the main issues in the industry that cry out for a DFMA solution. These issues, according to him, are mainly driven by the industry's tightening cost-to-performance targets, (as designers are no more able to play on the ground of compromising performance for cost and vice versa), its lack of supply chain transparency on what piece parts "should cost," and how to optimize those costs, along with maintaining delivery schedule slippage with in its tolerable limit (Dewhurst, 2010, Tsai, 2012).

According to Tsai (2012), gauging the progress made in incorporating DFMA with aerospace manufacture is sometimes difficult. This is mainly because of lack of adequate knowledge about the subject matter and reluctance to recognize the significant benefit that can be obtained from sharing and spreading the already constructed knowledge. As stipulated in Tsai (2012), the professionals in the aerospace industry are tight-lipped about what they do with the integration and application of DFMA tools. The company Boeing has made tremendous advancements in the integration of DFMA and Lean philosophies in its product developments and still it has unwavering strategies that are devised to make the industry more synchronized with the dynamics of customer demands. Often industries are outdistanced from one another in the achievement of assembly process efficiencies. Compared to the few DFM strides that have been achieved by manufacturers in understanding comparative material and process costs, little has been recognized as advancement in making DFA part consolidation an integral part of new product development, leaving the industry to face the difficulties and challenges associated with it (Tsai, 2012).

Potentially, DFMA has more to offer to aerospace manufacturers. Tsai (2012), in his explanation, has referred the aerospace industry for being resistant to the integration of DFMA systems. Despite the enormous price pressures and buyer expectations it now faces, in the regards of part count reduction analysis, aerospace industry is at its infant stage of development-almost at the place where consumer electronics firms were ten or fifteen years ago. As was explained earlier, a number of manufacturers are using the manufacture block of DFMA giving scant attention to the assembly block. It is apparent that, a product’s overall performance is an aggregated outcome of both the manufacture and assembly blocks of the development process. Misplaced priority and preference of one factor over the other leads to the question of whether the quoted part is fundamental, merely, to the product’s overall performance (Tsai, 2012). In this sense, fully integrated implementation of DFMA results in improved performance and great number of benefits can also be obtained. Tsai suggests that the industry needs to make part count reduction analysis a standard practice, so as to benefit the most out of DFMA.

Automotive industry

The history of design for Manufacturing and Assembly traces us back to the second world war, when Ford and Chrysler were using the principles to design and manufacture weapons, tanks and other military products (Sigo, 2007). Evolving to this stage, the styling of its cars, which is vital to attracting buyers, has been improved many times and generally becomes more aerodynamic (Fox et al., 2002).

White goods industry

The white goods industry refers to an industry operated by manufacturers of major home appliances as refrigerators, cookers, washing machines etc. (Kovalchuk, 2006). Applying the concepts of DFMA to a new part development, a local white goods industry could illustrate the advantages of a multidisciplinary part development. The task was substitute a complex assembly of different parts made of press worked metal and plastics by an aggregated function single solution with cost reduction, short-time tooling payback, quality improvement and mainly ease to assemble in line (Kovalchuk, 2006).

An important tool to win the battle of reducing parts there by saving costs and create an elegant design in the white goods industry is the rising sophistication in the use of moulded injection plastics (Kovalchuk, 2006). Plastic injected parts could consolidate several different other parts, that are made of plastics or not. What is rather a complex geometry to manufacture can be obtained in an injection process with relative ease (Kovalchuk, 2006). This results in savings of time to manufacture sub-assemblies and facilitates the mounting operation. Kovalchuk (2006) explains that the use of plastic multifunctional parts not only reduces production cycle of subassemblies but also improves the general quality of the product by reducing the probability of defective parts in the assemblies and the possibility of a mistaken coupling.

2.4 General DFMA criteria

There can be found a wide range of strategies, principles and guidelines that are formulated in a view to successfully implement DFMA. Some authors and industries present a rather detailed and fragmented strategy, while others consider DFMA principles in a more general and grouped manner. For example the framework of DFMA forwarded by Boothroyd and Dewhurst (1987 cited in Eskilander, 2001) consists of main principles, while strategies and principles presented by other authors and institutes, such as Kenneth Crow (1998) and University of California at Berkeley (1998), are fragmented into smaller pieces. However, due to their interconnectivity, certain similarities can still be drawn among them.

For some of the principles simple rules can be applied. For example, when an assembly part fails to fulfill one or a certain set of criteria, a design review may be required to decide on the elimination of the part or redesign it. Though, prior to undertaking the redesign or elimination measures, there should be a proper evaluation method based on the criteria set. Bringing these criteria/requirements to the forefront of the design phase will result in a well thought of plan with different alternatives on parts' features and product for saving time and money.

In general these criteria can be considered as qualitative description of design practices that support the principles of DFMA. They are intended to be used during design phase as a catalyst to brainstorm ideas, and identify beneficial practices from avoidable ones (Geng, 2004, Lahtinen, 2011). The following general DFMA criteria are a combination of the principles and strategies presented by Hamidi and Farahmand (2008), Geng (2004), Crow (1998) and University of California at Berkeley (1998).

Simplify design and reduce the number of parts

In the design phase, each part should be analyzed according to rules such as:

- Can the part be eliminated by avoiding fasteners?
- Can the part be combined with another part?
- Can the part be standardized? or
- Can the function be performed in another way?

If any of the rules can be applied, great deal of cost can be saved due to less amount of material used, easier assembly, less inventory cost and control, without compromising increased quality.

Reduced number of parts allows a simplified design as few fabrication steps are needed during manufacture. As the number of assembly parts goes down, the risk of committing errors during assembly will be minimized, and it permits an easier assembly and eventually disassembly process.

Standardize and use common parts and materials

This general DFMA criterion is a combination of material needs suitable for a fundamental performance-related reason and the need for use of standardized and identical assembly parts to produce non identical final products. , When similar materials are used for the manufacture of assembly parts, the parts will rather be monolithic and shear failure zones can be avoided.

By standardizing parts, the inventory costs can be decreased, also if processes are standardized; handling and assembly operations can be more effective. Consequently, Operator learning will be implemented easier. Furthermore, time and money can be saved in product development since additional experimentation is not needed.

When choosing materials, there are opportunities for introducing new material by innovation or substituting prevalent ones. Materials can be made to have the same appearance as the substituted ones, but can be less expensive or easier to work with. As a result, production cost can be decreased.

Mistake-proof product design and assembly (Poka-yoke)

Poka-yoke is a Japanese term designated for a system used for making sure that a product is assembled in the right way. Mistake-Proof products can be designed by allowing only a single way of assembly. If part of a product can only be assembled in a single way, the likeliness to make a mistake during assembly is highly reduced. This can be done by using: notches, asymmetrical holes and stops. in few cases error detection or mistake proof verification systems are implemented. This can be done, for example, with the help of alarm systems, clicking/snap-fitting sounds or application of tools that can only be used in certain sequence. If there is no one single way of assembly, then part design should incorporate symmetry around both axes of insertion wherever possible. Where parts cannot be symmetrical, the asymmetry should be emphasized by providing easily identifiable feature to assure correct insertion. .

Design for ease of parts orientation, handling and assembly

Designing assembly parts in a way that minimizes movement, rotation or other non-value-adding manual effort is crucial for saving time and cost. An example of this can be assembling parts from one direction (unidirectional assembly) or working with base components and solid mounting surfaces by using the advantage of gravity and keeping the largest mass on a low centre. During unidirectional assembly, the parts that are already assembled do not need to change their spatial position for the next parts to be fitted on them. This makes the assembly simpler, faster, and cheaper and brings overall efficient product development. Crow (1998) presents some basic principles to facilitate parts handling and orientation:

- Parts must be designed to consistently orient themselves when fed into a process.
- With hidden features that require a particular orientation, provide an external feature or guide surface to correctly orient the part.
- Guides should be provided to facilitate insertion.
- Parts should be designed with surfaces so that they can be easily grasped, placed and assembled. Ideally this means flat, parallel surfaces that would allow a part to be picked-up and easily connected.

- Avoid the use of small parts with thin and flat surfaces, as their assembly r requires the use of tools such as a tweezers Avoid parts with sharp edges, burrs or points. These parts can injure workers as they require more careful handling. They can also damage product finishes, and they are more susceptible for damage as they are features protruded from part surfaces.
- Avoid parts that can be easily damaged or broken.
- Avoid parts that are sticky or slippery. Such as thin oily plates and parts, adhesive backed parts, plastic parts with smooth surfaces, etc.).
- Avoid heavy parts that will increase worker fatigue, increase risk of worker injury, and slow the assembly process.
- Minimize flexible parts and interconnections. This includes avoidance of flexible and other vulnerable parts for example: belts, gaskets, tubing, cables and wire harnesses. Flexible features increases the risk of damage, and also makes the handling and assembly task more difficult.

Design for efficient joining and fastening

Fasteners are the connectors between different parts (e.g. screws, bolts, rivets and nails) which are time-consuming to assemble and difficult to automate. Again, with an efficient joining and fastening, complexity in assembly can be reduced, with that follows certain respective benefits.

There are a number of self-fastening connections that can decrease the handling time, for example snap-fits, sonic welding and adhesives. Furthermore, fastening techniques should be matched with material types, for easier disassembly and service functionality.

Design for manufacturing and ease of fabrication

The objective of achieving a simple manufacturing process is to minimize processing time while meeting the functional requirements. Design should have an objective of eliminating unnecessary parts, and avoid the use of complex tools etc.

Lower the need for screening and inspection by including allowable tolerances into the production process. Establish control of the production process capabilities and avoid tight tolerance on delicate elements of the assembly.

For such achievements considerations as stipulated in Crow (1998) need to be taken into account. The following list presents Crow’s machinability guidelines

- For higher volume parts, consider castings or stampings to reduce machining
- Use near net shapes for molded and forged parts to minimize machining and processing effort
- Design for ease of assembly by providing large solid mounting surface & parallel clamping surfaces
- Avoid designs requiring sharp corners or points in cutting tools – as such features can be broken easily
- Avoid thin walls, thin webs, deep pockets or deep holes to withstand clamping & machining without distortion
- Avoid tapers & contours as much as possible in favor of rectangular shapes
- Avoid undercuts which require special operations & tools
- Avoid hardened or materials difficult to manipulate unless they are mandatory due to specific requirements

- Design work pieces to use standard cutters, drill bit sizes or other tools
- Avoid small holes as drill bit breakage gets greater

Design to avoid unneeded surface finish requirements

When tolerance is tight, production processes will be difficult and the connectivity itself will be complex. During assembly, the tolerance problem can be solved by introducing features that guide the insertion such as chamfered edges, external guides and slots. In the absence of these guides higher tolerances make the assembly processes more difficult and put a need to undertake on-site surface finishing requirements.

2.5 DFMA: state of the art in the construction industry

It is beneficial to carefully study and identify factors and decisive criteria, as well as design and assembly methods that have successfully been adopted from other industries and applied in the construction sector. With a focus in the domain of DFMA, this can be accomplished by conducting literature studies on the application of DFMA in civil construction.

As mentioned earlier DFMA rules and principles are used by a wide range of companies in different industries (Fox et al., 2002). Part of the research question in this work is to what extent the principle can be applied in the construction industry in a view to bring the said efficiency in saving time and money. Considering the significant impact of design tasks on construction productivity and quality, it would be of great potential for the construction industry to integrate the principles of DFMA in its design phases where multiple decisions are passed (Fox et al., 2002).

For the reason that there are distinctive differences between the manufacturing and construction industry, one cannot simply apply methods used in other industries into construction without making some adoptions. However, there have been multiple studies on different design methods which are being transferred to the construction industry (Fox et al., 2002, Bibby, 2003). For example applying the lesser part thinking of DFMA into bridge building would induce difficulties in terms of transportation and handling, as parts of the product are scrutinized forging the part to a near-net shape from the start (Dewhurst, 2010, Herrmann et al., 2004). In construction, there has to be some kind of balance between bulky parts and assembly magnitude.

Concurrent Engineering has been an interest to the construction academia and practitioners for few decades (Khalfan et al., 2000). In earlier sections it is noted that DFMA tools are in place to integrate design and production considerations thereby assuring the achievement of objectives of Concurrent Engineering. On the other hand it is shown that design tasks are commonly performed by holding the design and construction processes separated and following traditional/sequential design approaches as reinforced by Fox et al., (2002) and an interviewee from Skanska. Khalfan et al. (2000) shows results from few case studies that are conducted to study the factors for readiness of applying Concurrent Engineering in the construction industry. The article concludes that the most important ingredient which promotes easy application is the people engaged in projects (e.g. teams in an organization), while the technological wing is the not as equally important in the subject matter. This leads to the need for continuous improvements in the management and governance styles of human resource. The results also reveals that among different parties engaged in construction projects sub-contractors show the most interest and readiness for the implementation of Concurrent Engineering. While clients and consulting organizations are observed to be moderate in the integration moves, suppliers and manufacturers portray a significantly low readiness factor (Khalfan et al., 2000).

Another design method which is used for improvement of construction processes is the implementation of constructability rules. By addressing production issues early in the design phase, these constructability rules bring the said improvements in design objectives from a production perspective (Fox et al., 2002). Constructability rules are easy to formulate and/or obtain, and they are meant to be used as set of guidelines compiled from some best practices in construction. A typical example of such a design objective can be "design for minimum time below ground". This design objective is clearly devised to avoid difficult and dangerous work situations (Fox et al., 2002). Some constructability rules are formulated in line with instinct of construction workers, thus tasks are seen to be accomplished without a need to follow lows and regulations. Such a thing can be for example, the use of concrete blocks instead of clay bricks. Due to their well-defined shape and form and also the possibility in their material type to manufacture bigger parts with reduced numbers, it is evident that concrete blocks are preferred to clay bricks as it is difficult to align them incorrectly during actual assembly.

Traditionally, the absence of constructability rules in design is blamed on the architects, that their lack of construction knowledge is the cause for problems in productivity and quality (Fox et al., 2002). According to Fox et al. (2002) even if there are quite a few successful computerized applications for design, they have only been linked separately to different stages of designs, not in a procedure which supports the concept of DFMA. On the other hand technology has advanced in the modeling aspect. 3D work and prototyping of designs are technically more feasible (Fox et al., 2002). These tools are developed further with fourth or fifth dimension, for example inclusion of time dimension in construction planning, making them useful tools for design methods to be applied better. Furthermore, it was concluded that actions can be taken to develop the constructability rules on a wider aspect and increase their success (Fox et al., 2002).

Constructability rules – field study

Using DFMA rules Fox, et al. (2002) performed a field study to investigate how rules applied could improve design to further create construction productivity and quality benefits. The study was tested on the design of assisted bathrooms contained within the bedrooms of a healthcare facility. The DFMA rules used were:

- Field study Rule 1: Ensure adequate access and unrestricted vision
- Field study Rule 2: Design parts that cannot be installed incorrectly

The DFMA rules were applied (see Table 2-1 & 2-2) and with an adoption of rule 2 into construction, a new constructability rule could be compiled (see Table 2-3). By discussing these rules with workers, questions could be formulated. Using these questions in a work breakdown process the two rules could be fulfilled in a successful way, which led to design improvements. As a result, reduced production time and cost were achieved. For example, the design improvements on the WC panels saved one man-week of work for the plumbing contractor. Another example is the reduction by 20% on the rework costs to wall vinyl welds and wall penetrations as estimated by the relevant specialist workers (Fox et al., 2002).

Table 2-1 Design improvements (source: Fox, 2002)

Rule applied	Detail	Design improvement
Rule 1: Ensure adequate access and unrestricted vision	WC panels Wall vinyl	Framing section reduced Weld moved from corner
Rule 2: Design subassemblies that cannot be constructed incorrectly	Floor screed Wall penetrations	Specific batch recipe defined Use of neoprene gaskets

Table 2-2 Construction productivity and quality benefits (source: Fox, 2002)

Rule applied	Detail	Benefits
Rule 1: Ensure adequate access and unrestricted vision	WC access panels Wall vinyl	Reduced production time and cost Reduced rework cost
Rule 2: Design subassemblies that cannot be constructed incorrectly	Floor screed Wall penetrations	Reduced production time and cost Reduced rework cost

Table 2-3 Sample new constructability rule (source: Fox, 2002)

Design rule	Design strategies
Minimize cutting by:	*Matching sizes of bespoke components with standard material sizes *Harmonizing the building's structural, envelope and internal grids *Positioning internal fittings within the building's partitioning grids

These constructability rules can be seen as an obvious procedure in construction. Yet, there is capacity to further develop the idea of using DFMA as design procedures or to compile constructability rules. Constructability rules have been available for a number of years, but compared to other industries, there have not been advancements in the construction industry to fully develop these rules into a framework (Fox et al., 2002). It is known that global competition, producer-led market specific design, and concurrent engineering are more prevalent in other industries (Boothroyd, 1994, Giudice et al., 2009).

However, one field study is not enough to make a general conclusion on the effectiveness of applying DFMA on constructability rules. By addressing the development of constructability rules, discussion can start and further improvements can be generated. For this, there is a need of pressure from e.g. clients. (Fox et al., 2002) also present guidelines for application of rules in a successful way:

Guidelines for successful application

1. *Focus rules on each design stage in sequence* – Which rules to use and in what sequence, during each design stage. Using DFMA, construction books, and production management knowledge to provide rules that will have an overall improvement on productivity and quality of the whole construction.

2. *Support rules with self-explanatory strategies and production database* – Provide guidance for designers, formulated by component designers with the revision of the construction manager and building designer. Especially in traditional procurement methods, rules should be integrated with production databases.

3. *Develop routine and foolproof application methods for rule* – Start with traditional manual, workbooks to develop knowledge-based engineering (KBE) software. These tools can have different factors built into it, for example production feasibility and safety risks.

4. *Target rules on best available productivity/quality improvement opportunities* – Formulate rules that fit the organization's opportunities without compromising the constructability of each building as a whole. Consideration needs to be taken between bespoke component and standard component, to design for manufacture and/or to simplify assembly.

There are several examples of bridge constructions that have gone through improvements in their design objectives. Some of the current advanced design tasks consider similar principles that are underpinned by DFMA systems. The design of integral abutment and jointless bridges is such an example, which envisages construction/ production costs and maintenance issues which are important part of sustainability (Mistry, 2000)

An integral abutment bridges are designed without expansion joints in the bridge decks, where thermal and braking loads on the superstructure are absorbed through the superstructure and abutments into the soil. In order to not overloading the abutment, the piles have to follow the bridge's deformation. Therefore only one row of flexible piles is used in each abutment. The downside of these bridges is that there is a limitation to the deformation of the bridge due to the method. Therefore, it is sensitive to temperature differences and the limitation of the span is depended on the geographical climate (Mistry, 2000). However the main benefits gained from the concept is a simple design that allows a faster construction, since fewer parts and piles are needed and back wall can be cast simultaneously. When replacing or constructing integral abutment bridge, it can be built around existing foundations without requiring complete removal of existing substructure (Mistry, 2000).

No joints and bearing are needed, which are expensive to buy, install, maintain and repair and even more costly to replace. Consequently one of the most frequent corrosion problems will not be prevalent anymore. This is due to leaking of expansion joints, allowing surface water with salt from the roadway to attack girder ends, bearings and supporting reinforced concrete substructures. With a smooth jointless construction, vehicular riding quality will be improved and diminishes vehicular impact stress levels. All these advantages lead to less construction and maintenance cost, furthermore less time spent on-site with production and higher quality is achieved (Mistry, 2000).

3 DFMA Criteria and PANTURA Indicators

Part of the task in this thesis work is to evaluate the assembly methods for their suitability in meeting the PANTURA indicators. This requires identification of a number of bottlenecks and vital criteria that are prevalent during the installation of bridges. These criteria will then be interpreted into the PANTURA indicators and will be used as process parameters that must be fulfilled for the bridge installation to be fast and efficient. This chapter will undergo through parameters that need to be considered when implementing DFMA in bridge construction. These parameters are drawn mainly from literature studies and developed by interviews that are conducted in a view to strengthen the knowledge and adapt the DFMA criteria for their use in the construction of bridges.

3.1 PANTURA indicators in bridge construction

Even though the workplace, composition of personnel and project context are set beforehand, construction projects are yet unique by nature (Larsson and Emborg, 2011), as the activities are dynamic and full of contingencies. Despite their uniqueness, certain general and common criteria can still be identified among different construction projects. These general criteria, therefore, can be taken into consideration and be applied regardless of the differences in projects and work settings. Such general/common criteria in bridge construction are set forward by project PANTURA. The PANTURA indicators presented in this section are demands put on the construction of bridges in a view to meet social, environmental and sustainability issues. The list of PANTURA indicators are:

1. Mobility
2. Lifecycle Cost
3. Time
4. Worker Safety
5. Safety of Residents
6. Noise Disturbance
7. Dust Emissions
8. Greenhouse Gas Emissions
9. Energy Use
10. Waste Reduction and Recycling

The indicators listed above are the basis for the evaluation method established in this thesis work, as the assessed assembly techniques and technical concepts will be evaluated for their performance in meeting the individual PANTURA indicators.

3.2 DFMA translation of PANTURA indicators

The DFMA criteria presented in Section 2.4 are general attributes that are considered during the implementation of DFMA principles in product developments. The translation of PANTURA indicators into DFMA criteria is accomplished by identifying measurable traits in each general criterion and assigning them to the PANTURA requirements. In order to facilitate easy tracking of desirable traits during product designs, the general DFMA criteria were carefully disintegrated and characterized according to measurable traits of DFM and DFA. As a result, the DFMA translation is completed by assigning DFM and DFA traits to each one of the PANTURA indicators.

3.2.1 Characterization of the general DFMA criteria

Multi directional visualization of the impact of each of the aforementioned general DFMA criteria is a key to realize how they directly or indirectly affect achievement of the PANTURA goals in relation to bridge construction. Proper understanding of the influence they impose enables reasonable allocation of weights before the actual evaluation of assembly techniques and technical concepts, which will be dealt in Chapter 5.

For the sake of convenient tracing of DFMA criteria back in the product design, the guidelines are categorized in accordance with their manufacturing and assembly characteristics, and are analyzed in their respective category. In the forthcoming section, it is important to note the dual properties of some of the DFMA criteria as they possess both manufacturing and assembly characteristics and potentially influence both blocks of a new product development.

The two subsequent tables will present a summary of the important DFMA criteria discussed in Section 2.4. Some exclusive manufacturing and assembly features of each criterion alongside with their respective desired and undesired attributes are pointed out and shown for further ease during assigning weights to each characteristic and scoring the assembly techniques. There can be enormous characteristics attributed to each general criterion but, here, only the characteristics that have a perceived direct relation with and effect on assembly process are considered.

Table 3-1 General DFMA criteria, their manufacturing characteristics and traits

General DFMA Criteria	Manufacturing Characteristics	Desired Traits	Undesired Traits
Simplified design for manufacturing	**Fabrication steps*	Few	Many
	**Performance of Parts*	Qualified	Defective
	**Compatibility of processes with materials and production volumes*	Compatible	Incompatible
Reduced number of parts	**Combining parts (mould one piece rather than two pieces)*	Combined	Disintegrated
Standardize and use common parts and materials	**Material types used in producing the parts*	Desired	Undesired
	**Need for additional Experiment*	No	Yes

General DFMA Criteria	Manufacturing Characteristics	Desired Traits	Undesired Traits
Mistake-proof product design	**Physiology of components (Leads to number of possible ways of Assembly)*	Only one	More than one
	**Design of notches, asymmetrical holes, external guides and stops*	Present	Absent
	**Design of parts which incorporates symmetry around both axes of insertion*	Yes	No
Design for ease of parts orientation, handling and assembly	**Property of surfaces and sizes of parts, so that they can easily be placed and assembled*	Graspable	Ungraspable
	**Parts that are sticky, slippery and with sharp edges, burrs, and points*	Absent	Present
	**Parts weight*	Light	Heavy
Design for efficient joining and fastening	**Match fastening techniques with materials*	Yes	No
Design to avoid unneeded surface finish requirements	**Tolerances*	High	Low

In a similar fashion as for the table above, distinctive assembly features of each general DFMA criterion are traced and listed alongside with respective desired and undesired traits for further ease in a segmental analysis and assigning of weights for each of the characteristics and scores during evaluation.

Table 3-2 General DFMA criteria, their assembly characteristics and traits

General DFMA Criteria	Assembly Characteristics	Desired Traits	Undesired Traits
Simplified design for assembly	**Assembly error*	Few	Many
	**Assembly ease*	Easy	Difficult
	**Disassembly ease*	Easy	Difficult
	**Need for more complex tooling due to unnecessary part features*	No	Yes
Reduced number of parts	**Assembly steps*	Few	Many
	**Number of fasteners in use*	Few	Many
Standardize and use common parts and materials	**Handling and assembly operations*	Standardized	Unstandardized
	**Operator learning*	Simplified	Complicated
Mistake-proof product assembly	**Assembly process*	Unambiguous	Ambiguous
Ease of parts orientation, handling and assembly	**Assembly direction*	Unidirectional	Multidirectional
	**Flexible and flimsy parts such as belts, gaskets, cables, and wire harnesses*	Absent	Present
Efficient joining and fastening	**Use of threaded fasteners (screws, bolts, nuts and washers)*	No	Yes
Unneeded surface finish requirements during assembly	**Guided insertion (for example: presence of chamfered edges)*	Yes	No

3.2.2 Translation of the PANTURA indicators

In order to facilitate evaluation of the techniques with respect to PANTURA indicators, each DFMA criteria along with their respective manufacturing and assembly characteristics are considered in conjunction with their perceived impact on the different indicators separately.

Description of the demands put on the construction of bridges (PANTURA indicators listed in Section 3.1) as described in Thodesen et al. (2011) is presented hereafter. Translation of the indicators into DFMA requirements has also been done alongside in order to assign DFMA behaviour for the respective indicators. The DFMA behaviours assigned to each PANTURA indicators are selections from the manufacturing and assembly characteristics of the general DFMA criteria presented in Tables 3.1 and 3.2. The translation has been done by describing each PANTURA indicators in terms of significant DFMA considerations and criteria in bridge construction.

a. Mobility

General Description: Mobility is expressed as the time elapsed during the transportation of a vehicle from one point to another on a given transport route. It is considered as highly important factor, especially in the construction planning of infrastructures such as roads and bridges, the closing of which highly impedes mobility of traffic. As already mentioned, during analysing this indicator, considerations need to be taken to civil engineering works influencing the transportation facility and cause pedestrian and/or vehicle lane closures (Thodesen et al., 2011). When there is less or no need for stacking a construction material on-site, there will be significant reduction in the probability of lane closures and mobility disruptions due to traffic bottlenecks created by the stored materials. Another aspect can be the need for frequent maintenance due to unwanted weak joints in the final product. Whenever there is the need for maintenance, there will also be a need to close the traffic to facilitate the maintenance work. The deployment of workers and machinery which occupies a great deal of space during construction activities makes mobility disturbance a point of interest in urban development.

Translation: The general DFMA criteria that are closely linked to mobility are:

- Reduced number of parts
- Mistake-proof product design
- Design for ease of parts orientation, handling and assembly
- Simplified design for assembly
- Standardize and use common parts and materials
- Ease of parts orientation, handling and assembly
- Efficient joining and fastening and
- Unneeded surface finish requirements

Unlike the above two PANTURA indicators, the DFMA characteristics used in the characterization of traffic mobility requirements are both manufacturing and assembly related as described below:

Property of surfaces and sizes of parts, so that they can easily be placed and assembled: Simple handling can be sufficient with graspable assembly parts, while ungraspable assembly elements may require deployment of more machineries and human work which makes use of wider urban space during construction.

Parts weight: Heavy machinery is needed for the handling, storage and assembly of heavy assembly parts. If the construction planning does not take these factors into consideration, the involvement of heavy machineries during loading and unloading puts a need for extra space. This as a result creates bottlenecks in a given traffic movement.

Assembly error: Depending on the time of realization of the assembly error, rectification works can be considered as maintenance activities. During rectification of assembly errors during service life, there may be a need to close lanes and interrupt the traffic.

Need for more complex tooling due to unnecessary part features: Careful handling and storage is required in order not to damage assembly parts with delicate features. In such circumstances, more number of machineries and construction workers come in play thereby seizing the traffic flow.

Assembly steps: The steps that need to be followed in order to complete an assembly cycle are also decisive factors in mobility. As the number of assembly steps increases, varied assembly parts need to be transported segmentally and different construction machineries may need to be employed for the handling of the varied parts in each assembly step. This is a potential cause for frequent lane closures due to temporary storage at work spots.

Number of fasteners in use: The direct relation between numbers of fasteners used during assembly steps and the number of assembly parts is a point of interest here. Increased numbers of fasteners imply the presence of large number of parts in an assembly. The need to accommodate these assembly parts in a confined area of storage can be a challenge without prior planning or lane closures.

The number of joints in an assembly can also increase with the number of fasteners used. These joints created by the fasteners create weak shear surfaces in the final product. Whenever a need arises for maintaining these weak zones, there is also a need to close lanes and temporarily interrupt traffic to facilitate the work.

Handling and assembly operations: Workers operating under unstandardized systems are likely to use excessive resources including machineries and construction materials. Due to the prevailing erratic nature of the construction activity, construction materials including assembly parts can be stored in different places thereby utilizing extra space which, otherwise, would have been used for accommodating diverted traffic etc.

Assembly process: The presence of non-value adding activities due to ambiguous assembly operations will cause unwanted movements of construction machinery and workers. This creates a situation where wide area of construction space being used unnecessarily, there by closing lanes and parking spots in the vicinity.

Assembly direction: When designing processes of assembly, enough attention should be given as to avoid multidirectional assembly requirements. When an assembly needs to be done from multiple directions, depending on the circumstances of the area in proximity, there is an associated need for traffic lane closure. Assembly direction needs to be adapted to circumstances of the construction site to avoid interference with existing traffic.

b. Lifecycle cost

General Description: It is a challenge to assess life cycle costs (LCC) since it requires prediction of fluctuating future and calculation of net present values. Nonetheless, calculation of LCC is an important part of considering the long-term issues and assuring sustainable development. Currently there are established methods and tools used for calculating LCC for civil engineering works so that comparison among different construction alternatives can be made (Thodesen et al., 2011).

When introducing new working methodologies into a system, the methods have to be evaluated for their performance in terms of the overall lifecycle cost. LCC includes all the cost associated with and incurred during the design life of a certain civil engineering work. Construction costs, social costs, operation costs, waste disposal costs etc. are integral parts of the LCC.

Construction and maintenance costs are the main pillars in the evaluation of the total lifecycle cost. Usually when there is a need to make a comparison between different construction solutions, similar work settings will be assumed and estimation of construction cost will be performed by a mere calculation of the required amount of construction material (e.g. concrete, piles, and reinforcement). The main factors accounting for approximately 50% (excluding foundation) of the total construction cost, in concrete structures, are reinforcement, formwork and in-situ casting (Simonsson and Emborg, 2007). Precisely, construction cost is mainly determined by the extent of work set on-site and the amount which is produced. As less time spent on-site with machines and workers, there will be a great deal of construction cost savings (Simonsson and Emborg, 2007, Rwamamara, 2010).

Maintenance costs need to be converted to net present values with an agreed internal rate of return for the design life of the civil structure. Maintenance costs have an indirect relation with quality of the final product. There is no common use of industrialized methods in different work settings; therefore the said quality can vary in different markets. For example products with different qualities can be obtained from using prefabricated elements or reinforcement bars (Simonsson and Emborg, 2007, Eriksson and Jakobson, 2009). Typically, products (specifically bridges) assembled from prefab elements have a weak failure zone, as connection surfaces or joints are created during assembly. Bridge elements (e.g. joints) are subjected to fatigue due to repeated impact loading from vehicular live loads, and expansion/contraction movements due to weather changes. These factors coupled with depreciation and corrosion problems increase the need for maintenance (Mistry, 2000).

Translation: The general DFMA criteria that are closely linked to lifecycle cost are:

- Simplified design for manufacturing
- Standardize and use common parts and materials
- Design for efficient joining and fastening
- Design to avoid unneeded surface finish requirements
- Simplified design for assembly
- Reduced number of parts
- Ease of parts orientation, handling and assembly
- Efficient joining and fastening
- Unneeded surface finish requirements

Both manufacturing and assembly characteristics have a tread on these general DFMA behaviours of lifecycle cost. The explanation of each characteristic is presented below:

Fabrication steps: As the lead time of the product increases with greater number of fabrication steps, part of lifecycle costs, such as direct construction/fabrication costs can be affected by the number of steps involved in a fabrication process.

Performance of Parts: Performance of parts is manifested by a defective or qualified final product. Defective product requires rectification and/or maintenance thereby affecting the lifecycle cost. Parts with the required quality yield a qualified final product which does not require frequent maintenance in its service life. In the case where individual assembly parts do not have the intended quality, the design life of the bridge could face significant reduction as integrity among the bridge parts is in question. There has to be a trade-off between the initial higher costs incurred during the extraction process and the longer life of the final product produced from costly materials. For example even if higher cost is incurred during extraction and moulding of steel, the material can be used with less requirement of maintenance during its lifecycle and it can even be recycled.

Compatibility of processes with materials and production volumes: The compatibility of materials used in the process of fabrication and the processes followed has also an impact on lifecycle cost. For example some materials used in manufacturing steps require only simple processing with simple machineries or even hand tooling. But if the actual manufacturing process uses big machineries for the execution of such simple tasks, the lifecycle cost will increase.

Material types used in producing the parts: This manufacturing characteristic also has a direct influence over lifecycle cost. Parts can either be manufactured from cheaper materials that are easy to extract, process and shape or materials that need expensive extraction, purification and moulding works.

Need for additional Experiment: When there is a need to undertake additional experiment for testing performance of produced parts, there will definitely be respective additional cost associated with it.

Match fastening techniques with materials: When fastening techniques are adopted in line with the type of material used for manufacturing the parts, the outcome of the assembly process will have a better monolithic nature. When a different type of material is used for fastening than the parent material, there will be a risk of quick failure and thus maintenance and re-work.

Tolerances: When a bridge assembly part do not have the required absolute fit due to tolerance issues, the entire structural system will be susceptible to frequent maintenance arose from quality deterioration.

Assembly error: Assembly errors trigger need for maintenance and rectification works thereby adding up lifecycle costs of the civil work.

Assembly ease: The easier the assembly process, the less the procedure requires involvement of expertise and extra intensive tooling. This lowers the cost incurred for involving professional personnel as existing workers can handle the operation with minimal training.

Disassembly ease: The easier the disassembly process gets, the more it becomes simple to operate. Easy and simple disassembly steps do not require involvement of extra machinery and heavy demolition. As a consequence workers can handle the operation with minimal dismantling effort which does not cause extra cost incurred for associated works.

Need for more complex tooling due to unnecessary part features: When extra care is needed in a view not to damage fragile and/or unnecessary part features, more complex tooling and delicate handling will be required. During this excessive complex tooling works, extra machineries and additional workers come in place and direct construction work will increase accordingly. Similarly if these unnecessary part features are subjected to damage they may also require extra replacement costs.

Assembly steps: The steps that need to be followed in order to complete an assembly cycle are decisive factors in determining lifecycle cost of a product or an assembly result. It is obvious that the more assembly steps in a system, varied assembly parts need to be transported segmentally and different construction machineries may need to be employed for the handling of the varied parts in each assembly step. This increases the construction cost during actual assembly.

Use of threaded fasteners (screws, bolts, nuts and washers): Activities performed during screwing, bolting, and riveting two or more assembly parts require use of extra tooling and physical effort. When compared to assemblies which make use of the advantage of gravity for locking mechanism, assembly methods with bolts and nuts requires spending of additional cost both in term of material and operation cost. This significantly increases the lifecycle cost of the assembly operation. The use of fasteners also puts a demand on maintenance which significantly affects the lifecycle cost.

Guided insertion (for example: presence of chamfered edges): On-site surface finish works such as chamfering and smoothening involve extra activities which make use of grinder and sandpaper machines. These activities have their own adverse effects on planned construction cost.

c. Time

General Description: Among the various reasons why time considerations are important are the effects of construction time on environmental wellbeing, cost and quality of the construction (Simonsson and Emborg, 2007). To minimize time spent on-site is to reduce cost incurring issues such as workers and machinery (Larsson and Emborg, 2011), societal disturbances such as noise, dust, longer traffic closures and emission of combustion gases. When time spent during construction can be controlled and reduced, weather dependent construction activities can begin during favourable weather conditions and completed within the same time interval planned. By this weather dependency of construction activities are no more eminent. Further, if time is decreased on-site, workers do not have to endure as much noise, dust and being in risk of traffic related accident (Eriksson and Jakobson, 2009). However, this indicator is solely to qualitatively address time required on-site.

Translation: Only manufacturing and assembly characteristics directly affecting the time spent on site are considered here. There are general DFMA criteria that can be traced for having an impact on time. These are:

- Simplified design for manufacturing
- Simplified design for assembly
- Reduced number of parts
- Standardize and use common parts and materials
- Mistake-proof product design
- Design for ease of parts orientation, handling and assembly
- Design to avoid unneeded surface finish requirements

There are also manufacturing and assembly considerations which characterizes this PANTURA indicator and each general DFMA criteria that have a perceived direct relation with time spent on-site. The explanation of the said characteristics is presented herein under.

Combining parts (mould one piece rather than two pieces): When bigger assembly parts are manufactured by combining smaller ones, there will consequentially be shorter time spent on site due to the less number of parts to deal with.

Physiology of components: This manufacturing trait is perceived to have a significant impact on worker safety. Physiology of components is an expression used for the physical feature of parts that result in a number of possible ways of assembly. Some parts can be manufactured in such a way that their physical feature allows different ways of assembly while there is only one single correct way of assembling them. A typical simple example of this can be, plugging yellow and red jacks into their respective slots while setting up a sound system. Had it been the jacks were not distinguished with different colourings, there would have been a possibility to wrongly plug them into the wrong slots. Even though, wrong plugging is not physically restricted, the sound system will not give the intended result unless one assembles them in the only one right way. Inherent mistake proofing can be attributed to an assembly system, by manufacturing assembly parts in such a way that there is only one possible and correct assembly alterative. Assembly mistakes during setting up a sound system can only be recognized when the assembly outcome fails to serve the intended purpose (i.e. not giving a sound). There are no differentiations in part features and/or physical restrictions in the jacks to avoid assembly mistakes. Thus identification of errors during the assembly process and swift addressing of mistakes is not possible. In a bigger perspective, such as bridge assembly, once the entire assembly procedure is completed it is difficult to address mistakes committed in earlier steps, and a trial to do so consumes great deal of time.

Design of notches, asymmetrical holes, external guides and stops: the incorporation of notches, additional holes, guides and stops greatly helps in minimizing assembly errors and thus rework needs which affects time.

Design of parts which incorporates symmetry around both axes of insertion: Mistake proofing in assembly processes can also be achieved by allowing multiple axes of insertion. When parts have a symmetrical feature in both axes of insertion, the assembly process will have an inherent mistake proofing attribute, as there is no mistake committed in assembling the part in either axes. In such a case less time will be spent in a trial to figure out correct orientation of the parts during assembly operations. The difference in this characteristic from *Physiology of components* is that parts can be assembled correctly in all possible alternatives.

Property of surfaces and sizes of parts, so that they can easily be placed and assembled: When parts are designed and manufactured in such a way that they have physical features such as a handhold or impressions for firm holding and hanging during assembly, they are said to be easy to grasp, thereby reducing time spent in firm tying. Relatively, graspable parts do not require a great deal of time to handle and operate than ungraspable ones.

Parts that are sticky, slippery and with sharp edges, burrs, and points: Due to such features of assembly parts as sticky and slippery surfaces and sharp edges, parts handling and operation can be a challenge. Activities of logistics, stacking, and assembly of parts can be more efficient and fast if there are not plenty of considerations needed in order not to damage parts due to their undesired surface features.

Parts weight: Handling heavy parts at a work site requires intensive physical work and heavy construction machinery usage. Light assembly parts require light machineries and are easy for faster handling on site.

Tolerances: When parts are manufactured in such a way that they inherit exaggeratedly higher tolerances, they will cause a need for on-site preparations and surface finish works that have their own respective time consumption.

Assembly error: As it was explained earlier, depending on where in the assembly process mistakes are noted, errors during assembly cause needs for rectification and re-work. As the number of errors during construction increase, there will be a greater chance for frequent rectification work needs, which slips the time to complete the construction project.

Assembly ease: The easier the assembly process is, the more the process becomes easy to internalize. Easy and simple assembly steps do not require involvement of expertise and workers can handle the operation with minimal adaptation time. When the assembly has easy guides and procedures to follow, then it is simpler to train workers about the specifics of the assembly in question. Assembly processes with easy guidelines and procedures have an inherent time saving attribute by avoiding risks of re-work needs linked to errors and faulty assemblies.

Disassembly ease: The easier the disassembly process gets, the more the process becomes easy to handle. Easy and simple disassembly steps do not require involvement of extra machinery and heavy demolition and workers can handle the operation with minimal time and effort during dismantling.

Assembly steps: The number of steps that need to be followed during assembly operations significantly determines the time required to complete an assembly cycle. In another sense, workers when shifting from one assembly task to the other, they are also likely to take an interval of time before they adapt the new assembly task. As a result, there is certain time wasted during the onset of initial tasks in each assembly step.

Number of fasteners in use: It is not difficult to see the extra work required when there is a need of using excessive fasteners and connectors during assembly. Depending on how the fasteners are designed to be used or provided being welded with assembly parts, numbers of fasteners used for assembly can be a time demanding issue.

Handling and assembly operations: When handling and assembly operations are considered, standardization of the process is at the heart. When an assembly process is standardized, the tasks can be accomplished at a relatively faster rate. Due to the routines, workers will also have a greater chance to internalize the tasks involved, thereby avoiding extra time spent in non-value adding activities due to unstandardized systems.

Assembly process: Ambiguous assembly operations make work areas unclean and erratic. As site workers do not have the clear picture of the tasks involved, there will consequently be increased rate of occurrence of trials and errors in an effort to figure out the correct assembly way. Assembly operations should be unambiguous for the system to save time invested in all these ambiguous tasks.

Assembly direction: When designing processes of assembly, enough attention should be given as to avoid multidirectional assembly requirements. When an assembly needs to be done from multiple directions, there is associated workers' and machinery movement from one side to another. This as a result causes an investment in extra time.

Guided insertion (for example: presence of chamfered edges): High tolerances in assembly parts causes on-site adjustment demands (e.g. surface finishing works) for a firm fit. During times when assembly parts does not fit to each other, for example due to sharp corners and dimensional alterations, on-site surface finish requirements may be required to allow the intended fit. On-site surface finish works involve activities such as cutting and smoothening, which make use of part of a construction which would have been used for more value adding activities.

d. Worker safety during construction

General Description: Design for ease of handling and manipulation leads to increased safety at a work site. The working environment on-site is more physically demanding than what is there in pre-conditioned in-door environment. There are several factors that subject workers to a risk of injury and danger. Conditions of the site including weather and traffic, machineries, noxious fumes or chemicals, working platforms such as scaffolding and placement of formworks, elements or materials that require complex handling and time pressure are some of the many. Dealing with some of these factors require inappropriate working positions and heavy lifts thus resulting in falling accidents, injuries and chronic pains, as the most common type of injury at work are strains and sprains (Rwamamara, 2010).

Worker safety on-site can be achieved, for example, by introducing advanced construction techniques that require less on-site preparation such as excavation and machinery usage; since these in turn reduce the human work required to handle the work. In case of some construction methodologies such as prefab, as structural elements can be casted off-site in a conditioned in-door manufacturing environment, risk of accidents associated with on-site operation can be significantly reduced. However, there is also a trade-off between the dangers caused during handling of readymade bulky structural elements and injuries associated with minor detailing works on-site, such as reinforcement placing and fastening.

Translation: The translation of this PANTURA indicator can be expressed in terms of few relevant manufacturing and assembly characteristics from a DFMA perspective. There are general DFMA criteria that can be traced for having an impact on worker safety. These are:

- Mistake-proof product design
- Design for ease of parts orientation, handling and assembly
- Design for efficient joining and fastening and
- Design to avoid unneeded surface finish requirements

There are also manufacturing characteristics under each general DFMA criteria that have a perceived direct relation with worker safety on-site. The explanation of each manufacturing characteristics is presented herein under.

Physiology of components: This can be made clear by using the earlier example which explains the setting up of a sound system with coloured cables and jacks. If there are number of possible ways of assembling the same part, workers are susceptible for making mistakes and cause needs of frequent rework. Mistakes are primary causative agents for hazards by making the assembly process susceptible for accidents. When frequent rework needs arise workers may also get exhausted due to mental fatigue making them commit more errors.

Design of notches, asymmetrical holes, external guides and stops: These manufacturing traits of a product prevents errors during assembly by guiding the assembly, allowing multiple correct assembly orientations, and producing a clicking sound when the part locks into its right fit. When assembling such parts mistakes will be avoided to a greater extent thereby reducing adverse effects associated with them.

Design of parts which incorporates symmetry around both axes of insertion: When parts have a symmetrical feature in both axes of insertion, the assembly process will have an inherent mistake proofing attribute, as there is no mistake committed in assembling the part in either axes. In such a case less human work and physically intensive work will be required as there is no need to re-orient the part during assembly operations.

Property of surfaces and sizes of parts, so that they can easily be placed and assembled: When parts are designed and manufactured in such a way that they have physical features such as a handhold or impressions for firm holding and hanging during assembly, they are said to be easy to grasp, thereby reducing accidents due to difficulties in handling and operation.

Parts that are sticky, slippery and with sharp edges, burrs, and points: Due to such features of assembly parts as sticky and slippery surfaces and sharp edges, parts handling and operation can be a challenge. Working in such a challenging condition will result in increased probability of hazard occurrence. Presence of sticky or smooth surface properties of assembly parts are undesired traits. With the presence of slippery surfaces, for example, there is a danger of parts escaping from the harness which keep them hanged on a crane or parts with sharp edges cause dangers to works as they require delicate handling.

Parts weight: Handling heavy parts at a work site requires intensive physical work and construction machinery usage. The more effort it takes to carry or handle the assembly parts, the greater the probability that muscle fatigue, strains or sprains will occur and endanger the worker safety.

Match fastening techniques with materials: The fastening techniques used during assembly need to facilitate easy lock and key fittings of the assembly parts without a need to engage extra man power. The need for an extra tool or work for fastening and worker to guide the joining may put worker safety in question.

Tolerances: Tolerance, in this thesis work context, can be expressed as the maximum permissible deviation in measurement that a product can have in relation to the required absolute fit. When parts are manufactured in such a way that they inherit exaggeratedly tight tolerances that are beyond the natural capability of the material they are made of, they will cause unneeded on-site preparations and surface finish works that results in increased treat for worker safety.

Few assembly characteristics that have a perceived direct relation with worker safety on-site are:

Assembly error: As it was explained earlier, errors during assembly are sources of problems in worker safety during construction. As the number of errors during construction increase, there will be a greater chance for injuries and hazards to occur due to unplanned rectification works.

Assembly ease: The easier the assembly process is, the more it becomes mistake-proof. Easy assembly techniques does not require involvement of expertise and workers can handle the operation with minimal training, thereby avoiding mistakes, unnecessary needs of rework and danger due to lack of knowledge.

Disassembly ease: Processes should not be designed only for easy assembly but also simple disassembly. The easier the disassembly process gets, the more it becomes simple to handle. Easy and simple disassembly steps do not require involvement of extra machinery and heavy demolition and workers can handle the operation with minimal dismantling effort which does not cause put worker safety in danger.

Needs for more complex tooling due to unnecessary part features: When extra care is needed in a view not to damage fragile and/or unnecessary part features, more complex tooling and delicate handling will be required. During this excessive complex tooling works, worker safety will be put in question.

Assembly steps: The steps that need to be followed in order to complete an assembly cycle are decisive factors in worker safety. Workers when shift from one assembly task to the other, they are likely to take an interval of time before they adapt the new assembly task. This makes the initial tasks in each assembly step mistake and danger prone. As the number of assembly steps increases, workers will be required to quickly adapt frequently changing assembly tasks and if failed to do so there comes the issue.

Number of fasteners in use: It is not difficult to see the extra work required when there is a need of using excessive fasteners and connectors during assembly. In some cases, the number of fasteners in an assembly has a direct relation with the number of assembly parts. When there are considerably great numbers of fasteners to use during assembly, there is also a risk of danger and hazard associated with it, as each fastener may require bolting, nutting, riveting or welding.

Handling and assembly operations: When handling and assembly operations are considered, standardization of the process is at the heart. When an assembly process is standardized, the tasks can be accomplished by different site workers without compromising the final product quality. Due to the routines, workers will also have a greater chance to internalize the tasks involved, thereby avoiding risks of accident associated with problem's in adaptation.

Operator learning: When the assembly has easy guides and procedures to follow, then it is possible to train the workers about the specifics of the assembly in question. Assembly processes with easy guidelines and procedures have an inherent mistake proof attribute and avoid risks of danger linked to errors and faulty assemblies.

Assembly process: Ambiguous assembly operations make work areas danger prone. As site workers do not have the clear picture of the tasks involved, there will consequently be increased rate of occurrence of non-value adding activities and trials and errors in an effort to figure out the correct assembly way. Assembly operations should be unambiguous for the system to be free of hazards and accidents.

Assembly direction: which one of the following tasks is easy and danger proof in a process of assembly?, stacking pieces vertically on top of each other or filling a void by trying to insert a piece from a different direction. When designing processes of assembly, enough attention should be given as to avoid multidirectional assembly possibilities. In a bridge construction, unidirectional assemblies provide the advantage of building scaffoldings only on either side of the construction activity, as it is possible to accomplish the assembly task from the same direction.

Flexible and flimsy parts such as belts, gaskets, cables, and wire harnesses: A certain assembly design should avoid the use of flexible and flimsy materials during actual assembly. Due to their looseness, flexible and flimsy parts are susceptible to misconnection and as their flexibility makes material handling and assembly more difficult, they make the entire assembly operation accident-prone and create hazardous conditions for workers on site.

Use of threaded fasteners (screws, bolts, nuts and washers): Activities performed during screwing, bolting, and riveting two or more assembly parts require use of extra tooling and physical effort. When compared to assemblies which make use of the advantage of gravity for locking mechanism, assembly methods with bolts and nuts have an inherent danger of failure due to involvement of a connector as third party to connect the two parent materials.

Guided insertion (for example: presence of chamfered edges): During times when assembly parts does not fit to each other, for example due to sharp corners and dimensional alterations, on-site surface finish requirements may be required to allow the intended fit. Parts without sharp corners and possessing chamfered edges are more assembly friendly than the ones which require on-site adjustment. On-site surface finish works involve activities such as cutting and smoothening, which makes use of grinder and sandpaper machines. These activities have their own adverse effects on site workers.

e. Safety of residents

General Description: Safety of residents is mainly expressed in terms of the number and frequency of accidents that occur in a given area of construction site. One of the factors that manifest safety of residents is automobile accidents. Safety of residents can be questioned when construction site work imposes an impact on the surrounding traffic. For example rerouted traffic from a construction area tends to merge multiple lane traffics into a single one thereby increasing the probability of accidents occurrence (Thodesen et al., 2011). Other residents' safety issues caused by construction activities can also be related to dust, release of undesirable chemicals and toxic by-products. Furthermore, prevailing disruptions to the daily urban life of residents (e.g. noise, vibrations, accessibility problems, distorted urban landscape) can also increase the probability of dangers due to accidents (Sebastian, 2011). The said urban disturbances prevail mainly due to construction activities that require intensive machinery usage and bulky preparation works. Thus simplified production systems need to be in place, as with simplicity of construction methodologies, the aforementioned urban disturbances will reduce significantly.

Translation: Few of the general DFMA criteria that characterize safety of residents are:

- Standardize and use common parts and materials
- Simplified design for assembly
- Mistake-proof product assembly and
- Ease of parts orientation, handling and assembly

Though there are manufacturing issues that have an adverse effect on safety of residents, there is a more direct relation between assembly works on site and safety of residents. Thus most of the DFMA characteristics traced in the characterization of this PANTURA indicator are assembly related, as described here after:

Need for more complex tooling due to unnecessary part features: In a certain assembly operation if there rises a need to use extra tooling, hanging devises and machineries such as cranes, the chance of accident occurrence get higher and safety of nearby residents and/or pedestrians in the vicinity of the construction site will be endangered.

Handling and assembly operations: The logic used in worker safety can also be used here. Due to the routines in a standardized assembly operation, workers will have easy time internalizing the tasks involved, thereby avoiding risks of accident associated with problems in tasks adaptation.

Operator learning: Simplified assembly operations are easy to learn and also involve simple tools and machineries. The combination of minimal machinery usage, operation easiness and workers' task proficiency sets up a working environment with less hazardous effects on residents' safety.

Assembly process: The presence of non-value adding activities due to ambiguous assembly operations will cause unwanted movements of construction machinery and workers in the vicinity. This puts safety of residents in question.

f. Noise disturbance

General Description: Quality and standard of living as well as security of residents and road users can also be questioned when the inherent welfare of a society is affected by certain obstacles such as nuisance from noise (Sebastian, 2011). The level of disturbances from noise is obviously an indicator of sustainable urban development. Nuisance from noise can either be simulated and calculated or measured at the area where construction work is executed. Hence, prevailing noise disturbances can be compared with the allowed levels in the given construction environment. Noise is a standard consideration during planning organization of a construction site. This planning makes use of thematic and descriptive maps of noise disturbances, acoustics studies, environmental impact assessments etc. (Thodesen et al., 2011). When considering assembly methods, the elimination (practically reduction) of the need for machinery, extra preparation works, transports etc. can greatly help in the reduction of the magnitude of noise disturbances for the adjacent environment (Sebastian, 2011, Mistry, 2000).

Translation: The general DFMA criteria that are closely associated with noise disturbance are:

- Simplified design for assembly
- Reduced number of parts
- Standardize and use common parts and materials
- Mistake-proof product assembly
- Efficient joining and fastening and
- Unneeded surface finish requirements

Most of the DFMA characteristics traced in the characterization of noise disturbance, are assembly related, the description of which goes like this:

Need for more complex tooling due to unnecessary part features: The need for more complex tooling using extra machineries and vehicles produces unnecessary noise and disturbs the surrounding at a relatively greater extent.

Assembly steps: It is obvious that the more assembly steps in a system, varied assembly parts need to be transported segmentally and different construction machineries may need to be employed for the handling of the varied parts in each assembly step. This increases the magnitude of nuisance from noise.

Number of fasteners in use: In some cases, numbers of fasteners used during assembly steps are related to the number of parts and number of joints. Here it is important to notice that it is not only the assembly process which creates noise disturbance, but also final products of the assembly process. Considering bridges with joints on their deck they are likely to produce repeated noise as vehicles pass over the joints on their surface.

Handling and assembly operations: When assembly processes are unstandardized, there is a greater probability of need to deploy different kinds of machinery that suits the assembly task associated with each process. Same outputs can be produced in different ways if assembly processes are not standardized. In such an unstandardized work settings workers will tend to use extra machineries and vehicles to move parts from place to place.

Assembly process: Non-value adding activities associated with ambiguous assembly processes are significant sources of unnecessary noise emitted to the surrounding environment, thereby lowering the standard of living.

Use of threaded fasteners (screws, bolts, nuts and washers): Extra tools used during fastening of screws, bolts, nuts and washers are also sources from which unwanted noises emanate.

Guided insertion (for example: presence of chamfered edges): The important aspects of this characteristic which cause the release of unneeded noise are the machineries (such as grinder and sandpaper machines) employed for the extra surface finish work required during actual assembly difficulty occurred due to the absence of chamfered and filleted edges.

g. Dust emissions

General Description: Sources for particulate matter emissions can be any kind of physical work on site and transportation activities involved in assisting the construction process directly or indirectly (Sebastian, 2011). Similar to noise, dust (particulate matter emissions) can be calculated, simulated or measured on site. Dust management plans aim to handle particulate matter emissions in relation to the surrounding environment. Dust emissions are climate dependent and therefore should be considered in accordance with climate of the environment in question. For example, considering Scandinavian construction, dust emissions are not considered as critical problems due to prevailing climate conditions (Thodesen et al., 2011).

Translation: Dust emissions are strongly related to material types and assembly methods used during construction. The General DFMA criteria that have a potential in reduction of dust emission are:

- Simplified design for assembly
- Reduced number of parts
- Standardize and use common parts and materials
- Mistake-proof product design
- Design for ease of parts orientation, handling and assembly
- Design to avoid unneeded surface finish requirements

From the manufacturing point of view, certain characteristics can be considered. These characteristics can be related to:

Combining parts (mould one piece rather than two pieces): The fewer pieces there are the lesser is the manual work on site (e.g. using less machinery) and therefore dust emissions.

Material types used in producing the parts: This characteristic has an impact on the extent of dust produced during construction. For example in relative terms an assembly process which uses porous materials produces more dust than when working with dense and rigid materials such as steel.

Parts weight: When working with heavier parts, there will be a need to deploy more machinery. It is evident that, the use of these machineries will produce dust.

From the assembly perspective, there are more aspects to consider. Yet, most of them are related to the physical work on site:

Assembly ease: Easiness of an assembly can reduce the need for physical work and intensive use of machinery, thereby avoiding sources of dust emission.

Disassembly ease: Easy and simple disassembly steps do not require involvement of extra machinery and heavy demolition. As a consequence possibilities for dust emission will be reduced.

Need for more complex tooling due to unnecessary part features: When there is no need for a more complex tooling, employment of machineries and need for physical work will decrease substantially. This can reduce physical work and use of machinery.

Assembly steps: By designing parts for few assembly steps, the extent of physical work needed and utilization of machineries can also be reduced.

Handling and assembly operations: Standardized assembly routines avoid unnecessary activities associated with erratic work patterns. This can create better routines and minimize dust emissions.

Assembly process: When an assembly process is ambiguous due to different reasons, more physical work will be used and machineries will be employed. Consequentially dust emission will suffer.

Guided insertion: Whenever there is a need to perform surface finishing works, there has to be minor cuttings and smoothening which has an effect on the amount of particulate matter emissions.

h. Greenhouse gas (GHG) emissions

General Description: In order to trace sources of greenhouse gas emission, we need to follow a holistic approach. This holistic approach has to take into account emissions experienced during all phases of a project, including emission during extracting, processing and transporting materials. In order to effectively trace and manage greenhouse gas emission sources, it is imperative to segment them into different scopes, such as emissions owned and controlled by the civil engineering work; emissions due to the use and source of electricity; and indirect emission such as emission from transport etc. (Thodesen et al., 2011).

Translation: Measurement of greenhouse gas emissions is a diffused task which requires extensive quantitative data and overview of the whole project, with respect to indirect and direct emission sources. Greenhouse gases can be emitted during consumption of energy. It is evident that higher energy consumptions can cause higher potential of GHG emissions.

The general DFMA criteria affecting this indicator are:

- Simplified design for manufacturing
- Simplified design for assembly
- Reduced number of parts
- Standardize and use common parts and materials
- Mistake-proof product design
- Design for ease of parts orientation, handling and assembly
- Design to avoid unneeded surface finish requirements

Depending on the types of materials and processes used during construction, there can be differences in extent of emissions. In this regard, manufacturing considerations have a major impact on GHG emissions. The following manufacturing characteristics are considered when translating this PANTURA indicator into DFMA:

Fabrication steps: Lean manufacturing process with few steps can save substantial amount of energy waste which can contribute to GHG emissions.

Compatibility of processes with materials and production volumes: With a compatible, smooth and Lean production processes and material usage, a significant amount of energy waste can be avoided.

Combining parts (mould one piece rather than two pieces): When parts are combined, the energy required for handling and operation will be less relative to a situation where there is a need to deal with smaller but plenty of parts. This in turn reduces the amount of GHG emitted from these processes. Combining parts in a manufacturing environment can also be a lot more energy efficient than attending the task on-site.

Materials types used in producing the parts: Considering material types is a very important part in the lifecycle analysis of energy use and greenhouse gas emissions. Certain materials can be energy efficient when the entire process from extraction to final material usage is considered.

Need for additional experiments: The need of prototypes for testing the performance of products may put a need to go for additional physical testing. Depending on the type of the additional experiment required, greenhouse gasses can be emitted from the processes.

Parts weight: Dealing with heavy parts contributes to higher energy consumption during transportation and logistics. Greenhouse gasses can be emitted from heavy machineries used during these logistic and operational activities

Assembly ease: Assembly processes can be easy in terms of the type of machineries deployed to handle the assembly tasks. Depending on the type of machineries deployed, different amount of greenhouse gasses can be emitted. The lesser the assembly effort the lesser the amount of energy consumed and thus GHG emitted.

Disassembly ease: Similar analogy can be applied here also. The lesser the disassembly effort, the lesser the amount of energy consumed and thus GHG emitted.

Handling and assembly operations: The development of standardized assembly operations creates easy routines for handling and operational efficiency thereby reducing the amount of energy consumed and thus GHG emitted. When processes are standardized workers can be trained to learn the operations easily and fast. By doing this, unwanted activities that consume energy can be reduced from the assembly system.

Guided insertion: Cutting, welding and smoothening works that are associated with on-site surface finish works have a potential of releasing greenhouse gasses.

i. Energy use

General Description: The indicator for energy use is bridge specific, as it includes the energy consumption experienced during the construction and demolition of the civil engineering work and all related manufactured components. The energy used is calculated or measured at hand. This indicator can be used for comparison between different bridge projects (Thodesen et al., 2011).

During measurement of energy use, further analysis is required to assess the environmental impact in the long run. When using methods that reduce construction time on-site (e.g. prefabricated bridge parts), consequences need to be considered. For example, due to the non-monolithic nature of precast bridges, consequential maintenance is required during the design life of the bridge. This scenario triggers extensive use of resources thereby affecting the environment. There are tasks of a construction process that are liable for higher energy use. These tasks are mostly linked with foundation excavations of soil masses and retaining structures and have a potential to increase the amount of energy used by construction machineries.

Translation: Similar to GHG emissions, the measurement of energy use requires overview of the whole project, consideration of various factors and extensive amount of data. The general DFMA criteria affecting this indicator are:

- Simplified design for manufacturing
- Simplified design for assembly
- Reduced number of parts
- Standardize and use common parts and materials
- Mistake-proof product design
- Design for ease of parts orientation, handling and assembly
- Design to avoid unneeded surface finish requirements

Fabrication steps: Lean manufacturing process with few steps can save substantial amount of energy wasted.

Compatibility of processes with materials and production volumes: With a compatible, smooth and Lean production processes and material usage, a significant amount of energy waste can be avoided.

Combining parts (mould one piece rather than two pieces): When parts are combined, the energy required for handling and operation will be less relative to a situation where there is a need to deal with smaller but plenty of parts. Combining parts in a manufacturing environment can also be a lot more energy efficient than attending the task on-site.

Materials types used in producing the parts: Considering material types is a very important part in the lifecycle analysis of energy use. Certain materials can be energy efficient when the direct operations in the entire construction process are considered.

Need for additional experiments: The need of prototypes for testing the performance of products may put a need to go for additional physical testing. Depending on the type of the additional experiment required, energy can be consumed during the processes.

Assembly ease: Assembly processes can be easy in terms of the type of machineries deployed to handle the assembly tasks. Depending on the type of machineries deployed, energy can be consumed at different levels.

Disassembly ease: Here the important consideration is what different machineries are required to accomplish disassembly task. A disassembly process can be difficult or easy in terms of the type of machineries deployed to handle the tasks. Depending on the type of machineries deployed, energy can be consumed at different levels.

Need for more complex tooling due to unnecessary part features: Equivalent energy consumption can be experienced following the magnitude of extent of tooling and machinery needed for handling complex parts.

Assembly steps: A process which requires higher number of assembly steps has more number of activities involved. Considering the entire assembly process, there will consequently be higher energy waste than an assembly step with fewer numbers of steps.

Handling and assembly operations: The development of standardized assembly operations creates easy routines for handling and operational efficiency thereby reducing the amount of energy consumed. When processes are standardized workers can be trained to learn the operations easily and fast. By doing this, unwanted activities that consume energy can be reduced from the assembly system.

Guided insertion (for example presence of chamfered edges): Assembly parts need to have the necessary surface finish features when they are manufactured. Parts with need of on-site surface finish requirements will put a demand of using tools and machineries. The use of machineries and tools on-site uses a higher amount of energy as construction site is a contingent environment and energy used during actual construction work is not as efficient as the ones executed in a controlled manufacturing circumstance.

j. Waste reduction/recycling

General Description: Waste management involves calculation, estimation or measurements of the amount of waste which is composted, reused, recycled, incinerated (or used as fuels) or disposed in a landfill. This can be measured by certain units. For example concrete (m3), asphalt (t), aggregates (m3), steel (kg).

There are uncertainties during the task of gathering or finding reliable information about materials used, recycled and wastes produced. Reports prepared on this area are mixed, inaccurate or inconclusive. One of the issues can be largeness of bridge construction projects and the situation that bill of materials often get blended due to the combination of different tasks that are intertwined. There are also difficulties in sorting and differentiating materials to be reused or disposed. Construction materials have to be standardized and readily available for usage. This can be done by giving them certain marking of where and when to use them. Converting volumes to masses for some of the materials also creates uncertainties in reports (Thodesen et al., 2011).

One of the common examples of waste generated during construction is a soil mass excavated during groundwork and deposited or disposed. The amount and type of waste generated is contingent upon the construction method used.

The circumstances of a working site can have an effect on material usage. Circumstances such as traffic conditions, urban development, landscape difficulties and weather conditions cause material damage. In a context of higher complex work site, handling and storing materials is difficult and materials will be more susceptible to damage. Therefore logistics in such conditions needs to be efficient and executed with care. These considerations should be assessed during the design of parts. Furthermore, contemplation of the possibilities for positioning cranes or loading/unloading areas is required for effective handling and avoidance of material damage (Pan, 2008, Thodesen et al., 2011). Other measures of avoiding damage can be the use of climate protective tent and make the construction process weather independent. Furthermore, IT and Lean construction tools can be used to keep an overview and control of resources and materials (Simonsson and Emborg, 2007).

Translation: Similar to greenhouse gas emissions and energy use, measurement of the amount of waste reduced or recycled needs multiple criteria considerations at the same time requiring a more reliable and informative data from the entire project.

The general DFMA criteria that have an impact on a project in relation to waste generation are:

- Simplified design for manufacturing
- Simplified design for assembly
- Reduced number of parts
- Standardize and use common parts and materials
- Mistake-proof product design
- Design for ease of parts orientation, handling and assembly
- Design to avoid unneeded surface finish requirements

The manufacturing characteristics found to be important in characterizing this PANTURA indicator are:

Fabrication steps: In the manufacturing process, short and small number of fabrication steps is desired as to reduce risks of faulty production and therefore waste generation.

Performance of parts: High performance can reduce, if any, the need for replacement of faulty parts. Depending on how these replaced parts can be reused the extent of waste generation may suffer.

Compatibility of processes with materials and production volumes: With a compatible, smooth and Lean production processes and material usage, a significant amount of waste can be reduced.

Combining parts (mould one piece rather than two pieces): When parts are combined, they will possess a more rigid character and delicateness of parts will be substantially reduced relative to a situation where there is a need to deal with smaller but fragile parts. This reduces the risk of damaging parts and thus avoids replacement requirements.

Material types used in producing the parts: The type of material which is used for the construction, highly determines the possibilities of recycling the material for further usage. As some parts made from certain material can be re-used while others have a deficiency in this regard.

Assembly error: Errors in an assembly process lead to damage in assembly parts and thus generation of wastes.

The following tables (Tables 3-3 and 3-4) present a summary of the translations of each PANTURA indicators into manufacturing and assembly characteristics. For the sake of easy tracking of the effects of manufacturing and assembly traits in each PANTURA indicators, two separate matrices are showcased according to the respective impact of the characteristics on manufacturing or assembly of parts. A mark "X" is used to show the relationship between a PANTURA indicator and the associated DFMA characteristics.

Table 3-3 PANTURA indicators - Manufacturing characteristics matrix

INFLUENCE MATRIX: PANTURA INDICATORS Vs. MANUFACTURING CHARACTERISTICS											
General DFMA Criteria	Manufacturing Characteristics	Mobility	LCC	Time	Worker safety	Safety of residents	Noise disturbance	Dust emission	GHG	Energy use	Waste reduction
Simplified design for manufacturing	Fabrication steps		X						X	X	X
	Parts performance		X								X
	Process compatibility		X						X	X	X
Parts number	Combining parts			X				X	X	X	X
Common parts and materials	Material types		X					X	X	X	X
	Additional experiment		X						X	X	
Mistake-proof product design	Parts' physiology			X	X						
	Stops, notches, guides			X	X						
	Axes symmetry			X	X						
Ease of parts orientation handling and assembly	Surface property	X		X	X						
	Sticky and slippery parts			X	X						
	Parts weight	X		X	X			X	X		
Efficient joining	Matched fastening		X		X						
Surface finishing	Tolerances		X	X	X						

Table 3-4 PANTURA indicators - Assembly characteristics matrix

INFLUENCE MATRIX: PANTURA INDICATORS Vs. ASSEMBLY CHARACTERISTICS											
General DFMA Criteria	Assembly Characteristics	Mobility	LCC	Time	Worker safety	Safety of residents	Noise disturbance	Dust emission	GHG	Energy use	Waste reduction
Simplified design for assembly	Assembly error	X	X	X	X						X
	Assembly ease		X	X	X			X	X	X	
	Disassembly ease		X	X	X			X	X	X	
	Complex tooling	X	X		X	X	X	X		X	
Reduced number of parts	Assembly steps	X	X	X	X		X	X		X	
	Number of fasteners	X		X	X		X				
Common parts and materials	Handling and assembly	X		X	X	X	X	X	X	X	
	Operator learning				X	X					
Mistake-proofing	Assembly process	X		X	X	X	X	X			
Parts orientation	Assembly direction	X		X	X						
	Flexible and flimsy parts				X						
Efficient joining	Threaded fasteners		X		X		X				
Surface finishing	Guided insertion		X	X	X		X	X	X	X	

4 Review of industrialized assembly methods

Different varieties of assembly techniques and methods of interest can be identified by conducting study visits, reading industry brochures, from electronic sources and careful day to day observations. Though, the most important achievement of this research is measured by the suitability of the methods for convenient evaluation. As a consequence, the required methods of assembly in this study are those with clear rules and procedures which makes simplifies identification of their features during the evaluation and ready for easy adoption into bridge construction. Some of such kinds of assembly methods are presented together with technical concepts developed for an easy assembly and construction of fibre reinforced bridges and bridge decks.

4.1 ConXtech structural steel space frame systems

ConXL^{TM} and ConXR^{TM} are the two innovative space frame systems devised by ConXtech, steel structures manufacturer based in the United States. The systems can be used for the construction of commercial office buildings, hospitals, blast resistance structures etc and are currently being used for the construction of naval lodges that cover up to 146,500 GSF whose framing is completed within 25 working days.

ConXtech's space frame systems deliver an innovative yet commercially viable alternative to traditional building methods. ConXtech devises a systemized approach to building design by utilizing the advantage of standardizing structural components and a wide range of robust connectors. This yields a simplified structural system that meets the required structural criteria simultaneously (JJeong, 2011). Apart from its suitability for shorter spanned structures and the use of bolts and fasteners in ConXR, the two space frame systems use similar assembly principles. Thus for the sake of demonstration of the techniques and avoid redundant evaluation, the ConXL framing system is used.

Its flexible configurability makes ConXL well suited to meet certain project requirements needed when constructing commercial and office buildings, hospitals, military structures, schools, parking tents, data centres and industrial markets. The ConXL System applies technology to the building industry and results in improved efficiency. This structural space frame systems approach is made possible by employing automated and efficient processes, from design through fabrication, shipping and field assembly (JJeong, 2011).

Apart from the structural viability of the system, the technology provided by ConXtech also allows simple integration of other modular or factory-built building components. The compatibility of the system with other modular structural parts is as such important and the inherent precision of ConXtech system allows this required compatibility (JJeong, 2011).

Key Advantages of the system

The benefits which can be sought from this structural system are presented in JJeong (2011). The ones which are in line with the focus and purpose of this master thesis are outlined herein under.

- The structural simplicity of the system does not compromise the robustness of the frame system. With its structural simplicity there is an inherent seismic, blast and progressive collapse resistance.

- The redundant distribution of moment frames can bring foundation savings and the easy installation lowers the assembly cost of the structural system. The aggregate of these two reduces total cost of the project (total installed cost) when compared to conventional structural alternatives.
- The simplicity and precision of the connection methods enables faster erection when compared to the traditional assembly with bolts and nuts. Rapidness of the construction can be improved two to five fold when compared to other conventional structural alternatives.
- On-site material handling and storage is minimized because of sequential delivery of structural components.
- By design, the ConXL system is made to eliminate the need for field welding. Structural components can be assembled by easily lowering and locking into one another at their joint spots.
- The system inherently prevents risks of error associated with on-site assembly. The joint spots are welded at their precise location as information from electronic CAD/CAM files and Building Information Models (BIM) are fed into the system. This thereby increases the precision of the assembly and reduces the risk of human error and need for rework.
- No bracings, diagonal members and shear walls are applied to ensure structural stability. This allows aesthetic and architectural design freedom.
- Despite the difficulty to maintain strict degrees of installation accuracy as listed on a design, ConXL has a superior dimensional tolerance to accommodate assembly inaccuracies. This Brings high quality, efficient installations and satisfactory tight fit.
- The demand to build high quality sustainable buildings is evident. ConXL System components are manufactured in a highly automated manufacturing facility where technology minimizes waste and carbon emissions. The simplified and easy on-site assembly requires minimal extent of human labor and construction equipment usage resulting in a reduced carbon footprint. The system also makes use of durable materials; that are efficiently designed both for assembly, disassembly and reuse.

Core Frame Components

The structural frame of a building constructed by the ConXL system is referred to as a "Chassis", as the system simplifies the structural frame to a unified system of beams, columns and other structural components. This "chassis" comprised of a finite set of systemized components:

a. HSS tube or built-up box columns (see Figure 4-1)

Figure 4-1 ConXR and ConXL columns (JJeong, 2011)

b. Wide flange beams (see Figure 4-2)

Figure 4-2 ConXR and ConXL wide flange beams (JJeong, 2011)

c. Two patented interlocking joints, one which forms a bi-axial moment connection (collar), and the other an innovative gravity connection. Both connections are easily assembled by lowering and locking beams into place on-site and require no field "cut-and-fit" or welding associated with conventional steel systems (see Figure 4-3).

Figure 4-3 Connection Collar (JJeong, 2011)

4.1.1 On-site assembly techniques for composite FRP-steel bridges

The following technical concepts are developed for the construction of composite FRP-steel bridges and are proposed for use in projects that are in line with PANTURA goals. The bridge concepts are composites of high-performance construction materials, such as fibre reinforced polymer (FRP) composites and steel girders. In the last decade, the use of FRP composite materials has grown widely in bridge construction and one application of composite materials for bridges is FRP decks lying on conventional steel girders. Composite FRP decks rested on steel girders are appealing in new construction of bridges where the demands are fast erection time, light weight and corrosion resistance. Therefore the development of on-site assembly techniques, such as the technical concepts presented hereunder, are points of attraction in the contemporary construction industry.

a. Technical concept 1: Snap-fit connection between FRP deck and steel girders

The connections between the girders and the deck are conducted by snap-fit connections. Snap-fit steel tubes are welded on the girders. Holes are cut from the bottom plate of the deck and the deck is fitted from above. The holes in the bottom flange are not cut at the intersection points between the flanges and the webs of the decks but on the hollow sections. The connection is illustrated in Figure 4-4.

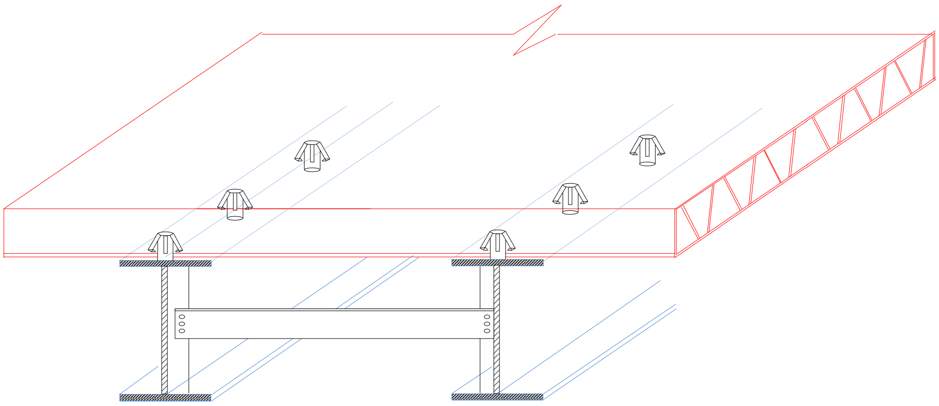

Figure 4-4 Snap-fit connection between steel girders and FRP deck

The procedures prescribed for this technical concept are:

1. FRP deck is prefabricated in panels with the holes cut on the bottom flange and delivered on-site
2. The snap-fit steel tubes are welded off-site and transported to the site
3. After the steel girders are brought in place, the FRP deck is lifted and pressed to the girders

b. Technical concept 2: Bolted connection between FRP deck and steel girders

This connection concept is done by means of bolts welded on the longitudinal steel girders and FRP sections with holes cut on the top flanges where the bolts are inserted (see Figure 4-5).

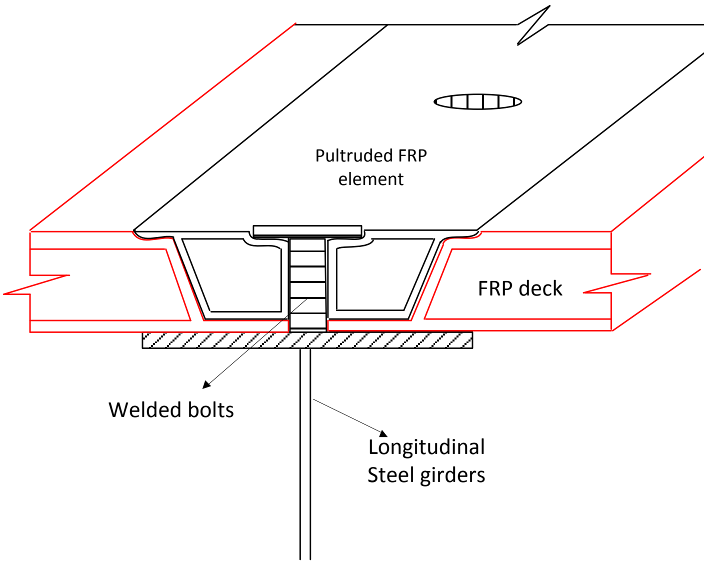

Figure 4-5 Bolted connection between FRP deck and the steel girders

The steps of installation for this connection are:

1. Bolts are welded to the steel girders off-site and lifted to place
2. Decks are lifted and rested on the steel girders
3. The FRP element is inserted and the bolts are fastened on-site

c. Technical concept 3: Shear-stud connection between FRP deck and steel girders

This concept is developed for bridges where transverse steel girders are utilized as load-bearing members as well (see Figure 4-6 and 4-7).

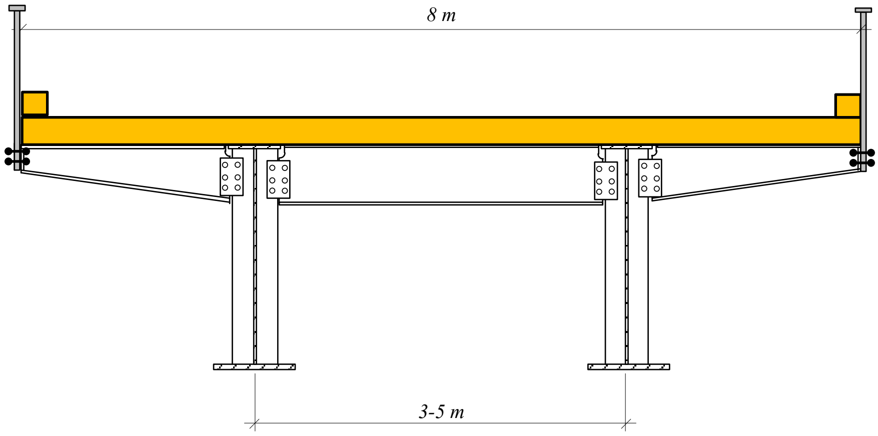

Figure 4-6 Cross-section of the bridge concept

The girders (transverse and longitudinal) are manufactured off-site with shear studs, concrete and a box of FRP plate with webs as shown in figure 4-7 below in order to connect the deck panels.

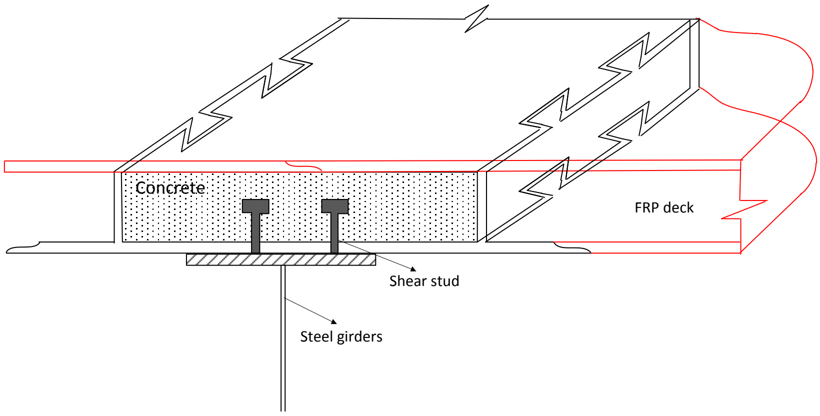

Figure 4-7 Connection detail for technical concept 3: Bidirectional deck with composite action

The deck panels are pre-fabricated with the same connections to fit into the girders. The panels are inserted from the top as illustrated in figure 4-8.

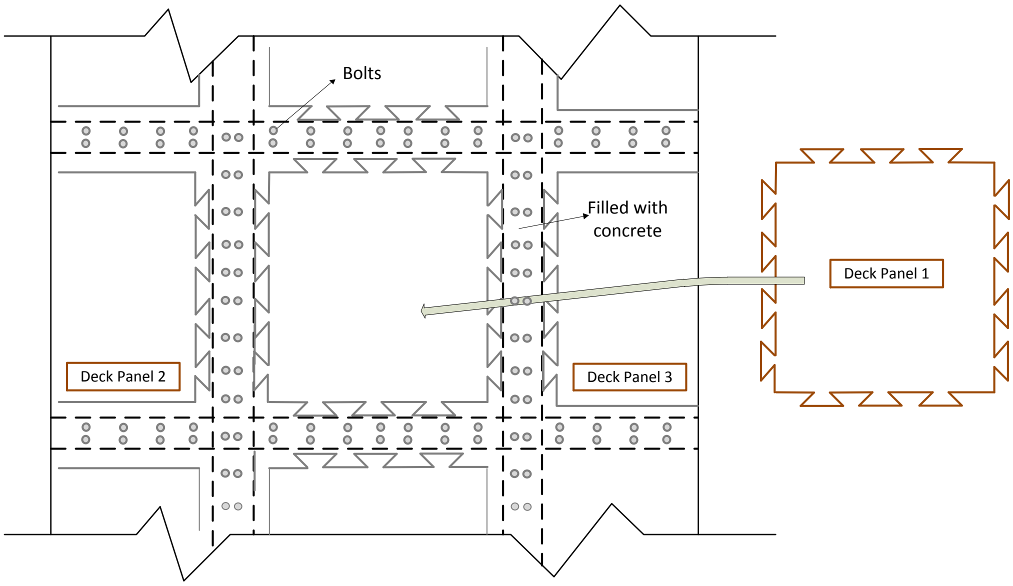

Figure 4-8 Illustration of insertion of deck panels to the superstructure

d. Technical concept 4: Bar-and-slot and snap-fit connections between FRP deck panels

There are two different deck-to-deck connection methods categorized under this technical concept. Bar-and-slot connection system is materialized by means of a bar-and-slot which resembles ball-and-socket joint. In this connection method each panel is slide onto the previous one by tilting it 45 degrees, inserting the bar in the slot, and letting self-weight close the connection. Furthermore, this connection acts transversally as a joint, allowing the deck to adapt longitudinally to girder deflections.

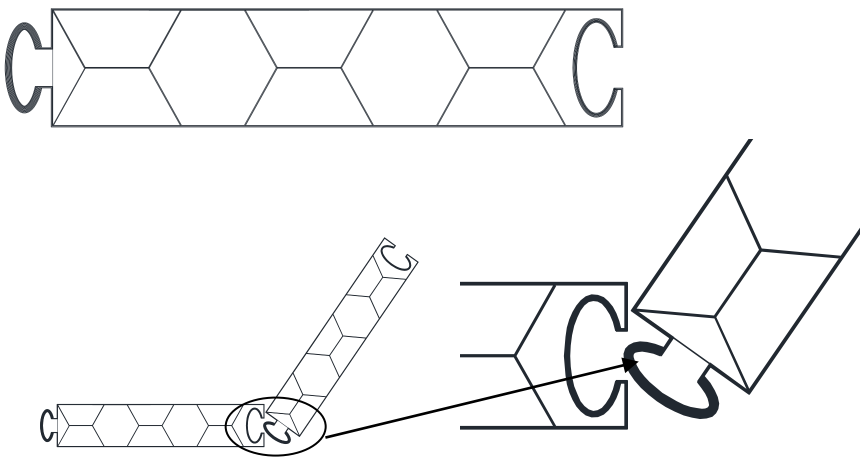

Figure 4-9 Bar-and-slot deck-to-deck panel connection

The other deck-to-deck connection is materialized by means of a snap-fit system, so that once deck sections are placed, interaction between twin tongues and grooves fixes relative displacements lengthwise of the bridge. Crosswise relative displacements are prevented by the deck to girder connection.

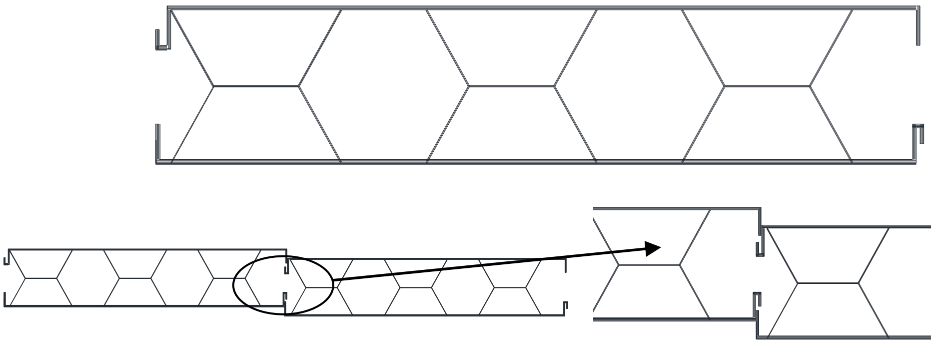

Figure 4-10 Snap-fit deck-to-deck panel connection

5 Evaluation Methods

Evaluating a phenomenon (specifically an assembly method) requires the use of certain parameters which make use of a framework of predefined criteria. If results of an evaluation are to be compared, there shall be similar ground on which the different scenarios are measured. The comparison between the general performances of the different assembly techniques presented in Chapter 4 is beyond the scope of this work, as they are applicable in different work settings and project conditions. In this section, an evaluation platform will be established based on which the assessed assembly methods and technical concepts are evaluated. The knowledge inseminated in earlier chapters about the principles of DFMA, PANTURA requirements and assembly methods and techniques will be used integrally in this section to establish the evaluation setup. The DFMA characteristics presented in Section 3.2.1 will be used as criteria when evaluating the assembly methods or technical concepts. Analogously, the assembly methods and technical concepts are also required to fulfil these criteria in order for them to be DFMA supportive.

5.1 Approach and choice of evaluation method

As stated by Daetz (1987 in Eskilander, 2001), in order to achieve consistent quality in products, certain attributes of interest have to be measured and results have to be tracked to maintain quality or bring further improvements. In a multi criteria industry, drawing these attributes of interest can be a challenge as there is a web of varied aspects and interests from the actors involved in the construction context. In such a situation, it is imperative to devise and follow a structured approach towards the challenge.

5.1.1 The approach

In order to successfully evaluate the assembly methods and technical concepts, it is vital to know the requirements of the assembly process in question. For example considering the assembly of prefabricated concrete elements, it involves handling of large and heavy concrete members. This can be presented as one of the bottlenecks in the assembly process. According to an interviewee from NCC, in situ casting of concrete, on the other hand, may have an inherent construction difficulty during reinforcement placing and fastening. Due to the obvious variation in work settings between the two, the bottlenecks associated with the respective construction methodology are also different in type. In a view to lay common playground for the assembly methods to be assessed without limiting the extent of the research, only on-site assembly or installation of bridge parts is considered.

According to Eskilander (2001), there can be used different approaches of evaluating a product, *quantitative or qualitative*. A *quantitative evaluation* involves measuring the performance of a product or a system (e.g. in terms of the time required and cost incurred for execution of a certain task). In an assembly perspective, quantitative evaluations do not provide specific and objective advices and procedures to design parts for an efficient assembly system. Apparently a DFMA tool gives an indication or qualitative information on how complex a product is, from an assembly point of view, in order to render it simpler and consequently making it less expensive (Lahtinen, 2011). The mere numerical results from a quantitative evaluation do not provide explicit information about the preferred solution for the assembly process (Eskilander, 2001).

A typical example of quantitative evaluation method is the one forwarded by Boothroyd and Dewhurst (1987 presented in Eskilander, 2001). In order to measure the performance of a design and product from an assembly view point, the method, in this example, uses a DFA index given by the equation,

DFA Index = $\frac{N_m \times t_m}{t_a} \times 100$

Where: Nm = theoretical minimum number of parts

tm = ideal minimum assembly time per part

ta = estimated total assembly time

According to the equation, a design or a product with low index, experiences at least one, two or all of the three downsides in its system, while a high index value shows a design that is optimal in the aspect of assembly. These downsides can be a large number of parts, extended assembly time per part and extended total time required for the assembly of the entire product. The results of the DFA index are then used to determine which scenarios require careful attention and pass preliminary decisions to eliminate or redesign the redundant assembly part (Geng, 2004), which requires extended time of assembly and incurs extra cost.

As shown by the example above, a quantitative method requires numerical data and parameters of measurement, and in output it provides a numerical estimated time and cost (Jürisoo and Staaf, 2007). These results have to be interpreted for their implication in the manufacturing or assembly.

On the other hand, a *qualitative measure* is based on a set of criteria or conditions that a product preferably should fulfill to fit in an assembly process. It can involve certain steps of measuring how far the product is from the ideal solution (Eskilander, 2001). An ideal solution in this thesis work refers to an assembly technique which fulfills all the DFMA characteristics translated into each PANTURA indicators. The process and assembly part feature considerations employed in qualitative evaluations makes it preferable for studies and researches aiming to provide explicit information about preferred solutions for assembly processes.

It is evident that, not all DFMA criteria can be fulfilled by a certain assembly technique, leaving it difficult to make relative judgment among the different techniques. Thus, when conducting an evaluation with qualitative measures, performance comparison will rather be made with the extent to which the DFMA behaviors in each PANTURA indicator are fulfilled by the assembly methods. So in this work, similar ideology of qualitative evaluation is considered as in Eskilander (2001), in which qualitative evaluation is performed based on a set of criteria that is used to decide if the assembly method does satisfy the DFMA characteristics used in the translation of each PANTURA indicators.

The following figure shows the procedure and flowchart used in the evaluation of the assessed assembly methods and technical concepts. Treatment of the subjects in each box constitutes the different chapters and sections in this thesis work.

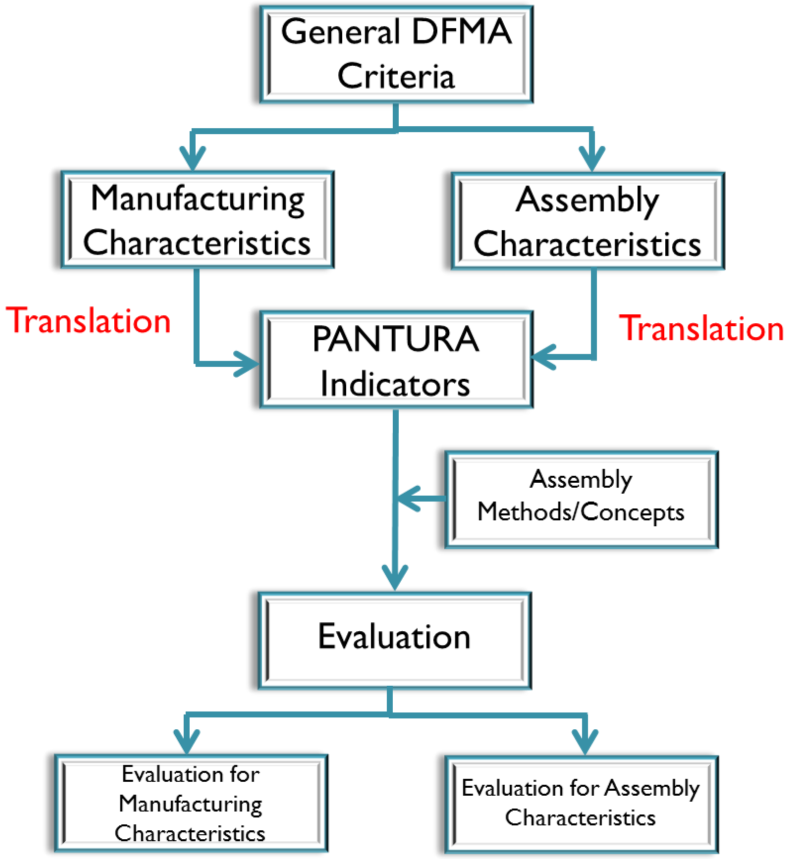

Figure 5-1: Evaluation flowchart

5.1.2 Choice of evaluation method

According to Eskilander and Carlsson (1998 stated in Lahtinen, 2011) and Harik and Sahmrani (2010), an applicable DFMA tool should fulfill the requirements listed herein under. These attributes can be considered as critical success factors for a successful implementation of DFMA method.

Table 5-1 DFMA critical success factors and their attributes

Critical success factors	Attributes
Present a non-patterned approach to problem solving	Qualitative and Quantitative
Include rules and techniques that will facilitate economic manufacture and improve assembly techniques at reduced cost, and easy handling of components	Qualitative
Promotes appropriate selection of materials and processes	Qualitative and Quantitative
Support for cross-functional teams	Qualitative
Enable transfer of knowledge	Qualitative
Include cost analysis	Quantitative
Include product's quality assurance	
Include views of manufacturability and assembly evaluation	Qualitative and Quantitative
Provide design suggestions and desirable solutions	Qualitative
Prohibit unnecessary design variants	Qualitative and Quantitative
Be user friendly	Qualitative and Quantitative

An ideal DFMA method should include the aforementioned requirements in order to enable evaluation of a design, manufacturing or assembly process and provide suggestions for possible improvements in a successful way (Lahtinen, 2011). As depicted in the table, for its successful application, DFMA should follow an equally qualitative approach towards the evaluation of products and methods (Eskilander, 2001) so as to provide design suggestions and desirable solutions that solves problems in the area they are applied.

There are certain criteria and indicators that are framed in the PANTURA context. The construction or assembly of bridges has to take these indicators into account, for it to be successful in meeting the PANTURA goals. According to the detail description of PANTURA indicators in Section 3.2.2, apart from quantitative measures most important of the indicators such as total life cycle cost, workers' and residents' safety, construction noise, traffic mobility, construction dust, carbon footprint and waste also require a significant qualitative analysis.

For the fact that great deal of cost is incurred during the assembly block of a construction (Jürisoo and Staaf, 2007) and due to the more qualitative feature of the

PANTURA requirements, coupled with the possibilities in qualitative approaches to analyse assembly processes and pass recommendations on features of an assembly part, exclusive emphasis will be given to assembly processes experienced during actual construction. The scope of this chapter will be restrained to qualitative evaluation of the assembly methods and technical concepts presented in Chapter 4.

5.2 Qualitative methods of evaluation for manufacturing and assembly

As it was explained in earlier section, the evaluation guidelines used in DFMA methods follow a more qualitative strategy. So far developed DFMA methodologies are qualitative and are often based on descriptive general guidelines (Harik and Sahmrani, 2010). In such cases of qualitative measurement, a profound knowledge and experience of designers, assemblers and manufacturers is crucial (Harik and Sahmrani, 2010). In qualitative evaluations, products are assessed for certain performance indicators in the different levels of the design process (Giachetti, 1999). Evaluations are conducted to assess the subject matter according to few criteria, which are compiled from certain objectives, and propose the most front ranked conceptual design (Lahtinen, 2011).

To recapitulate, when Concurrent Engineering is in place, assembly issues will need to be brought in the design process of the parts. The criteria considered when evaluating a certain assembly method/process should also include parameters that belong to both the manufacturing and assembly phases. When other industries refer to manufacturing, they are simultaneously considering the assembly process inherent in the production of goods or parts. On the other hand, even though tasks in traditional construction are usually performed on-site, contemporary construction industry is undergoing a far more different experience. For a better demonstration, consider the construction of a civil structure by using prefab concrete elements. Due to the bulkiness of the assembly parts (e.g. prefab concrete slab of a bridge deck), their manufacturing has to be done off site. This gives the construction industry a unique feature as the manufacturing of the prefab elements and the sequential assembly process are two physically separated but mutually influential tasks. Thus, when dealing with DFMA in construction, there should be a more customized approach towards setting criteria that exclusively belong to the manufacture and assembly blocks. But it is not easy to define such a criterion that has an exclusive influence either on manufacturing or assembly blocks of a construction. With the difficulties associated with it, this thesis makes use of the separate manufacturing and assembly characteristics that are already discussed in Section 3.2.1 and 3.2.2 as a basis for the evaluation of assembly methods and technical concepts.

According to Harik and Sahmrani (2010) and few more literatures, there are various types of DFMA methods in place. Despite the variety of their approach, all of them share similar concepts; in a way that they evaluate processes and results with respect to certain common requirements that need to be fulfilled. The various DFM, DFA or DFMA methods uses a combination of different design objectives such as Quality Function Deployment, manufacturing analyses, design to cost, parts interchangeability, manufacturability, interactive creation of geometric models, and design to feature recognition and generate proposals to re-design. Of the several methods discussed in different literatures, in this thesis work, a qualitative method of evaluation which is analogous to the method underpinned by Harik and Sahmrani

(2010) will be followed. Primarily, the separate treatment of manufacturing and assembly characteristics for the evaluation of methods and processes emanates from the method of evaluation used in Harik and Sahmrani (2010). The method first identifies important criteria then assigns weights to the respective parameters as to portray their effect on a given assembly process or method. Similarly in this thesis work, assignment of weights to each individual manufacturing and assembly characteristics is performed in order to reflect their perceived relevance in bridge construction and the subsequent influence they impose on the respective PANTURA indicators they are categorized into.

5.3 Assignment of weights and value engineering

In this section, detailed explanation of two separate weight studies and the method chosen for scoring the assembly techniques will be presented. As it was explained in earlier sections, the evaluation platform developed in this thesis work is a combination of the method underpinned by Harik and Sahmrani (2010) with evaluation criteria from DFMA studies (presented in Chapter 2 and 3) and a different choice of assignment of weights.

There were various difficulties encountered during characterization of the general DFMA criteria. Due to their intricate nature and dependability among each other, it is practically difficult to draw a clear distinctive line between the different general DFMA criteria and find exclusive traits and characteristics for each of them. Thus, assignment of weights for each characteristics and traits may require a subjective approach based on experience and importance of the traits in bridge engineering. As there is limited background on this area of study in the construction sector, there is little or no benchmarking by which such studies could easily grasp an already established knowledge for an improved adoption and implementation. In order to compensate the risk of biased evaluation outputs due to weights emanating from inexperienced and unfounded decisions, narrow range of weights is used. The weights assigned to each manufacturing and assembly characteristics ranges from 1 to 5 depending on the weak or strong influence they impose on the respective PANTURA indicators they are translated into. When evaluating an assembly method for a specific PANTURA indicator, the characteristics that are considered to be directly linked to the indicator in question can be weighted highly, while the ones which have a weak link with their parent indicator will be weighted as 1.

The following tables (Table 5-2 and 5-3) summarize the weights assigned to each manufacturing and assembly characteristics under the individual PANTURA indicators. The weightage reflects the perceived direct/strong or indirect/weak link between the characteristics and respective impact of the characteristics on manufacturing or assembly of parts.

Different stakeholder groups, decision makers and design professionals may tend to have varied interests and perceptions about the individual impacts of the DFMA characteristics on the PANTURA goals. As a result they can assign different values of weights depending on experiences in their fields of expertise. The assumption that lays the basis for the weighting in this specific context of the thesis work is presented in Appendix A.

Table 5-2 Weights assigned to manufacturing characteristics

WEIGHTS: MANUFACTURING CHARACTERISTICS											
General DFMA Criteria	Manufacturing Characteristics	Mobility	LCC	Time	Worker safety	Safety of residents	Noise disturbance	Dust emission	GHG	Energy use	Waste reduction
Simplified design for manufacturing	Fabrication steps		5						3	3	1
	Parts performance		5								3
	Process compatibility		2						3	3	1
Parts number	Combining parts			5				3	2	2	2
Common parts and materials	Material types		5					5	5	5	5
	Additional experiment		1						1	1	
Mistake-proof product design	Parts' physiology			2	3						
	Stops, notches,			1	1						
	Axes symmetry			1	1						
Ease of parts orientation handling and assembly	Surface property	2		2	4						
	Sticky and slippery parts			3	5						
	Parts weight	5		3	5			2	3		
Efficient joining	Matched fastening		4		1						
Surface finishing	Tolerances		2	1	1						

Table 5-3 Weights assigned to assembly characteristics

WEIGHTS: ASSEMBLY CHARACTERISTICS											
General DFMA Criteria	Assembly Characteristics	Mobility	LCC	Time	Worker safety	Safety of residents	Noise disturbance	Dust emission	GHG	Energy use	Waste reduction
Simplified design for assembly	Assembly error	5	3	3	5						3
	Assembly ease		1	2	3			1	2	2	
	Disassembly ease		2	1	4			3	2	2	
	Complex tooling	4	1		2	3	3	2		1	
Reduced number of parts	Assembly steps	4	1	1	1		2	2		1	
	Number of fasteners	3		1	1		3				
Common parts and materials	Handling and assembly	2		2	3	2	1	1	1	1	
	Operator learning				1	1					
Mistake-proofing	Assembly process	1		1	1	2	1	1			
Parts orientation	Assembly direction	5		3	4						
	Flexible and flimsy parts				4						
Efficient joining	Threaded fasteners		**2**		**1**		**1**				
Surface finishing	Guided insertion		**1**	**1**	**2**		**1**	**1**	**1**	**1**	

For ease of analysis and demonstration, the desired and undesired traits of an assembly method (shown in Table 3-1 and 3-2) are given with a score of 0 and 1 respectively according to what has been observed in the assembly method in question. For example, if an assembly method or technical concept is perceived to possess a desired trait it will attain a score of 1. Whenever undesired traits are noticed, the respective assembly method gets a score of 0.

5.4 The evaluation and interpretation of results

In order to be able to avoid as much subjective considerations as possible, certain assumptions are made. These assumptions are important to consolidate series of uniform considerations when evaluating the assembly techniques. There are factors that are perceived to have the potential of deviating results of the evaluations. One example of these can be work settings in which the assembly processes are assumed to take place. Work settings do have a significant influence on the efficiency of an assembly process. A typical manifestation of this is the efficiency level which can be obtained by implementing improved assembly techniques such as automation and the use of robots. Automation can increase efficiency of assembly or at least may bring the same result as what would have been accomplished by reducing the number of parts to be assembled (Sigo, 2007). Manually workers are more flexible than mechanical assembly equipment and therefore the demands and consequently the criteria for designing the product for manual assembly are different from that for automatic assembly (Eskilander, 2001). So it is mandatory to consider similar work settings when evaluating an assembly method as this helps to possess an easy control over the results of the evaluation. So this thesis work assumes manual assembly methodology (involving handling and tooling) for the analysis and evaluation of the assembly techniques. In other words manual assembly methodology is taken as the common work setting when assembly techniques are analyzed and evaluated.

The evaluation of the assessed assembly techniques was made in a table format containing the important parameters, characteristics and criteria that are listed in Tables 3-1 and 3-2 and weights summarized in Tables 5-2 and 5-3. As shown in the referenced tables, the manufacturing and assembly characteristics forms the general DFMA criteria for the construction/assembly of bridges and be the basis of evaluation of the techniques of assembly. The evaluation of the assembly techniques is performed by assigning scores to the respective manufacturing and assembly characteristics translated into PANTURA indicators. In Appendix B sets of tables showing the evaluation of each assembly techniques are presented. The tables are structured in such a way that the general DFMA criteria and respective characteristics with assigned weights of their perceived impact on the indicator in question are shown together with a scoring based on the desirability or undesirability of the assembly techniques in meeting each specific manufacturing and assembly characteristics. The evaluation has been done separately according to both manufacturing and assembly requirements. Later in the process, results of the evaluation under each PANTURA indicator has been aggregated to see how much an assembly technique fulfills the DFMA requirements mentioned under each PANTURA indicator.

For the sake of demonstrating final results of the evaluation, the aggregated scores attained by each assembly method and technical concept are presented in table 5-4.

Table 5-4 Summary of evaluation

SUMMARY OF EVALUATIONS

TECHNICAL CONCEPTS 1-4 & CONXL

	General DFMA Criteria	Manufacturing Characteristics	Mobility	LCC	Time	Worker safety	Safety of residents	Noise disturbance	Dust emission	GHG	Energy use	Waste reduction
TC1	*Total Score (Manufacturing)*		5	2	10	18	0	0	10	5	2	5
	Max Possible (Manufacturing)		7	11	18	21	0	0	10	5	2	10
	Total Score (Assembly)		16	9	14	28	8	9	8	4	6	3
	Max Possible (Assembly)		24	11	15	32	8	12	11	6	8	3
	Total Score (Manufacturing and Assembly)		21	11	24	46	8	9	18	9	8	8
	Max Possible (Manufacturing and Assembly)		31	22	33	53	8	12	21	11	10	13
TC2	*Total Score (Manufacturing)*		5	2	10	13	0	0	10	5	2	5
	Max Possible (Manufacturing)		7	24	18	21	0	0	10	17	14	12
	Total Score (Assembly)		20	9	15	31	8	11	11	6	8	3
	Max Possible (Assembly)		24	11	15	32	8	12	11	6	8	3
	Total Score (Manufacturing and Assembly)		25	11	25	44	8	11	21	11	10	8
	Max Possible (Manufacturing and Assembly)		31	35	33	53	8	12	21	23	22	15
TC3	*Total Score (Manufacturing)*		0	0	5	7	0	0	8	2	2	5
	Max Possible (Manufacturing)		7	24	18	21	0	0	10	17	14	12
	Total Score (Assembly)		7	6	10	22	5	8	5	1	3	3
	Max Possible (Assembly)		24	11	15	32	8	12	11	6	8	3
	Total Score (Manufacturing and Assembly)		7	6	15	29	5	8	13	3	5	8
	Max Possible (Manufacturing and Assembly)		31	35	33	53	8	12	21	23	22	15
TC4	*Total Score (Manufacturing)*		5	6	15	13	0	0	10	5	2	5
	Max Possible (Manufacturing)		7	24	18	21	0	0	10	17	14	12
	Total Score (Assembly)		24	11	15	32	8	12	11	6	8	3
	Max Possible (Assembly)		24	11	15	32	8	12	11	6	8	3
	Total Score (Manufacturing and Assembly)		29	17	30	45	8	12	21	11	10	8
	Max Possible (Manufacturing and Assembly)		31	35	33	53	8	12	21	23	22	15
CONXL	*Total Score (Manufacturing)*		2	11	15	13	0	0	5	5	5	8
	Max Possible (Manufacturing)		7	24	18	21	0	0	10	17	14	12
	Total Score (Assembly)		20	11	15	31	8	7	9	6	7	3
	Max Possible (Assembly)		24	11	15	32	8	12	11	6	8	3
	Total Score (Manufacturing and Assembly)		22	22	30	44	8	7	14	11	12	11
	Max Possible (Manufacturing and Assembly)		31	35	33	53	8	12	21	23	22	15

For the explanation of how the evaluation process works and how results can be translated, we can take the evaluation of one of the techniques for a certain PANTURA indicator during both blocks of manufacturing and assembly. As can be noted in the table, results of the evaluation are presented as a score attained by an assembly method out of a maximum possible that can be achieved. For example if the evaluation of technical concept 1 (TC1) for mobility during its manufacturing phase is considered, one can see from the summary table that it attains a score of 5 out of a possible 7 (that means 5/7). Considering the process of assembly using the same technical concept, mobility is said to be interrupted by 33, 33%, as the score attained by the assembly method in question is 16 out of a maximum 24. Here it is worth demonstrating that an ideal assembly method which results in a virtually no traffic disruption during assembly process has to reveal a result of 24/24. The other evaluation results can also be interpreted in the same way. Finally the scores attained by each assembly methods for every indicator during both manufacturing and assembly are summed and portrayed as a result which shows how much is the assembly method in question is supportive to a specified PANTURA indicator in a DFMA manner. As to reinforce this interpretation of the results, it is again important to consider an example. Considering the same example used earlier, Technical Concept 1 attains a result of 21 (5+16) from a total maximum of 31 (7+24). This result shows the extent to which the assembly method in question fulfils the requirements of mobility in a DFMA manner.

Evaluation results of the other assembly methods and technical concepts can be interpreted in the same way for each PANTURA indicator in relation to manufacturing and assembly processes. Results of the evaluation can thus be compared in three different levels by making use of manufacturing considerations, assembly considerations and DFMA considerations. Results of each PANTURA indicator for manufacturing, assembly and combinations of the two can be compared with their respective piers for other technical concepts.

6 Discussion

The tasks that have been covered in this thesis work are intertwined with each other, leaving the explanation of the different parts a challenging task without mentioning the relation with the others. The following section reflects upon the importance of this thesis work, difficulties encountered during the course of the work and the results that have been achieved.

From a general perspective, the aim of this master thesis is to devise and test a method of assessment of bridge assembly techniques that contribute to sustainability in urban environment. During the course work certain challenges were encountered impeding the fulfillment of the aims to the desired extent. Among the various obstacles, the most important ones are the difficulties faced during tasks of reviewing design methods and criteria for bridge construction, customizing/translating other industry concepts and transferring knowledge into construction, searching applicable and developed assembly methods, finding appropriate evaluation methods, and finally performing the actual evaluation. There are only few previously conducted works or already established knowledge that can be related to most of the tasks in this master thesis. For example, the transformation and application of DFMA as a design method and an evaluation tool in the construction industry is a recent development. Therefore undertaking such a task should be executed with all the necessary care. Furthermore, the results obtained from such a study should be open for discussion in order to be able to funnel more ingredients into the tasks for the betterment of the results. Certain major points could be raised in conjunction with the aforementioned tasks and are discussed below.

The aim of identifying manufacturing and assembly design principles for construction industry use requires performing a task of transferring the knowledge of design methods and objectives in other industries. This in turn requires a widespread study of literatures concerning design objectives and manufacturing-assembly principles. Furthermore, with a focus on bridge construction, there is a need for an understanding of the bottlenecks and criteria applicable for the subject industry. The design method that is underpinned in this master thesis is a design decision support tool which has been used and proven for its contribution in reducing cost, cutting wastes and bringing system efficiency. However, the true essence of DFMA applications is not clear and their cost-benefit analysis does not present a vivid picture of application costs being lower than benefits attained. This, perhaps, leaves a potential risk for users of the tools. Moreover, the literatures researched in the area of DFMA are mostly written by founders of the concept and are obviously favoring the application of the associated tools regardless of different industry settings.

As they are formulated to be applied in a different production scenario, the principles and guidelines followed in other industries when working with DFM, DFA, and DFMA methods portray a setup which is different from what is needed in the construction. Therefore selection of design criteria and objectives has been made based on their usefulness and applicability in the context of on-site bridge assembly. The choice and selection is based on an acquired knowledge in the area of bridges construction. Performing such a task of selection requires a profound experience and knowledge in the subject matter as there are plenty of assumptions to make and multiple decisions to pass. Due to this fact, the principles of DFMA can be applied in many different perspectives according to what is being perceived by each practitioners involved in the task of devising such design methods. Apart from this, some of the principles and guidelines are less important to be considered in the design and assembly of bridge parts. For example compared to the material types used in manufacturing or number of assembly parts, additional experiments needed for testing the performance of components does not have major effect on actual assembly on-site and impose a low weighted impact on some of the PANTURA indicators directly related to on-site construction processes.

Another challenge in the implementation of DFMA systems is the difficulty to focus on a single project phase while working with such a system in construction, as DFMA covers the entire project cycle (from design to assembly). It is also a challenging task to synchronize between construction processes and DFMA systems because construction process normally involves physically separated tasks which puts an obstacle to implement DFMA systems in their natural iterative way. Re-consideration of criteria seems to be only possible among construction projects while undergoing certain project learning activities. But short and swift iterative processes between manufacturing and assembly of construction elements within the same project can be a challenge.

There are still more aspects to contemplate concerning the application of the design methods into construction industry. Issues such as procurement systems that affect the extent of involvement of professional personnel and client/project owners' readiness and patience to introduce such revolutionary changes are out of the scope of this thesis work. Yet it is worth mentioning them briefly as they include important concerns that put a demand on the current procurement systems being employed. For example the absence of adequate incentives or lack of procurement system integration for designers to work in collaboration with professionals from the different phases and parts of projects in conjunction with the short time spent in the entire process of procurement leaves a difficulty in the implementation of design methods such as DFMA, as also stated by the interviewee from Skanska. To realize the benefits of DFMA, engineers have to be able to perform designs for multiple criteria objectives. For this, incentives and the required time for such extra measures has to be granted in the procurement system thereby triggering designers to consider production issues early in the product realization phases, so that important criteria such as in DFMA can be achieved and societal issues prescribed in performance indicators like PANTURA will be met.

Another setback is testing a conceptual design. Due to project specific issues a construction design performed according to DFMA systems cannot be tested in the same way as a small manufacturing product design routine would. However, the usefulness and applicability of DFMA can be enhanced with the integration of 3D and information modeling tools by allowing multiple criteria considerations early in the design phase to assess and visualize the entire project form beginning to late stages.

The process of translation of the DFMA criteria into PANTURA indicators was limited to a scenario where there is a perceived direct and strong relation between the DFMA criteria and the PANTURA indicators in question. This avoids presence of similar effects of characteristics in different PANTURA indicators thereby preventing similar characteristics from being evaluated multiple times and result in a distorted evaluation outcome. When devising the evaluation platform, the main issue was finding an evaluation method which fits in the objectives set, since the PANTURA indicators possess both qualitative and quantitative features. In accordance with the range of available knowledge and data, a qualitative evaluation approach was chosen, as it can be executed in a more simplified way and within shorter time than required by a quantitative one, where data collection, categorization, analysis and manipulation is an important aspect. The need of a deeper knowledge and project experience was also reflected while choosing and working with an evaluation method. Part of the evaluation process involves assignment of weights to the DFMA characteristics and scoring the methods of assembly which requires a well-founded understanding on the severity of each criterion in relation to bridge requirements and PANTURA goals and also great deal of experience in bridge construction. Due to the assumptions made during the course of evaluation, results of the evaluations performed in this thesis work reflect a more subjective approach and evaluation results may portray different numerical outputs according to the level of knowledge and experiences in working with the assessed assembly methods and the weights given to each evaluation criteria. But results of such an evaluation will remain to be subjective and open for discussion unless tasks of scoring and assignment of weights are inspired by a well-founded technical ground.

After presentation of few conceptual assembly techniques and methods to industry practitioners involved in project PANTURA, some of them were decided to be not in line with the primary objective setup at the commencement of this master thesis, which are types of assembly methods from other industries that are well developed with clear rules and procedures and ready for evaluation and easy adoption into bridge construction. Apparently, most of the technics researched during the course of this thesis work were at their early conceptual stages which make it difficult to draw conclusions on how they appear to be during actual assembly and see their applicability in bridge constructions without conducting further development.

Even though the combined effect of all these challenges cast its own shadow during the course of this thesis work, there are important areas of strength and observed applicability potentials of the concepts developed. The significant concepts that are put forward in this research are the DFMA criteria used in the evaluation. These evaluation criteria are presented as simplified demands that a product has to fulfill in order to achieve an efficient and easy assembly system which does not cause rework needs and assembly difficulties. Even though it is a challenging task to directly adapt assembly techniques to construction industry usage, the guidelines and criteria used during evaluation can be considered back in the design tasks when designing bridge assembly parts.

The other manifestation of the significance of this research is the possibility to attribute the conceptual and more theoretical PANTURA indicators with tangible and measurable DFMA behaviors. This allows the evaluation methods to be more applicable in the real world as the criteria used are features that can be observed and learnt from experience in working with different assembly methods.

Few implications were also observed during the trials to improve the quality of the evaluation results. As it was mentioned repeatedly, results of the evaluation are highly dependent on the assignment of weights to the evaluation criteria and scoring of the assembly methods. It would have been possible to achieve a more applicable and realistic result if weights of the criteria were assigned in conjunction with decision makers and industry practitioners. Looking into possibilities of evaluating with intermediate scores, other than “0” and “1”, in a qualitative approach would also benefit this thesis work as it helps to score methods in a way which better portrays their actual performance. Finally, funneling as many number of evaluation features as possible helps to frame a better set of desired manufacturing and assembly characteristics, thus the PANTURA indicators can be translated more objectively and evaluations undertaken in such a context will be more portraying real situations as they are freed from bias and distortions.

7 Conclusion

A mere focus on reductions in direct costs and on time accomplishments through rigorous checking of assembly activities has been a common practice in the construction industry. When considering other sustainability concerns, for example minimization of issues such as human work, traffic disruption and related social costs, different approaches of attaining these needs should be followed. In this research another dimension of resource efficiency and cutting costs has been assessed and made possible by the use of DFMA methods. Even if it requires great deal of initial investments, DFMA significantly facilitates attainment of the said goals for organizations and firms who work in line with sustainability objectives.

As it has been repeatedly mentioned, there is a challenge in designing a product and assembly process that fulfils all the DFMA requirements simultaneously. In such circumstances, it is suggested to prioritize and categorize the criteria according to requirements of stakeholders such as society, clients/owner, and environment. Such an approach can ease decisions on what relevant objectives to consider during design tasks. In conjunction, evaluations that rely on such criteria and objectives will have their own influence on stakeholders at different levels. The same analogy goes to the PANTURA indicators, as categorization of each of them according to stakeholder preferences will lead to unbiased and realistic interpretations of the evaluation criteria prescribed and results shown in this research. Moreover, early identification of desirable product characteristics, product assembly issues and social cost considerations is crucial for the construction industry to enjoy swift assemblies on-site and address related concerns.

As it was manifested during the evaluation, further guidelines, product feature requirements and improvement statements can be drawn for further developments of the concepts and assembly technics. This attribute makes the prescribed DFMA criteria applicable beyond a mere evaluation but also as suggestions for further improvements in product developments.

It is evident that such industrial thinking and advanced design methods as the assembly techniques and concept of DFMA have a contribution during brainstorming new objectives and ideas to multi-faceted design tasks. It can also be concluded that DFMA concept directs designers to do things the right way instead of doing the right things, as the iterative procedure supported by the system allows a better understanding among the actors involved, thereby feedbacks from every levels of product development can be taken into consideration during redesign processes. With this iterative nature of the task, industry practitioners will be able to enjoy the possibilities of testing, selecting and developing best practices from all possibly available “right ways of doing things”.

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APPENDIX A:
COMMENTS OF VALUES OF WEIGHTS

Contents

Appendix A: Comments on values of weights

a. Mobility

Characteristics	Comments
Surface property:	The effect is vague, handling difficulty may not trigger machinery usage but it triggers human work
Parts weight:	Obvious direct impact due to requirement of heavy machinery
Assembly error:	Obvious direct impact due to lane closures during maintenance
Complex tooling:	Highly affects mobility when parts are difficult to store and the required number of machineries for the task
Assembly steps:	Obvious direct effect due to temporary storages for each assembly step
Number of fasteners:	Use of fasteners in the long run triggers maintenance requirement
Handling and assembly:	Standardized systems enable efficient use of work site for storage and assembly
Assembly process:	Has a minor impact on mobility due to unwanted movement of workers and machinery.
Assembly direction:	Multidirectional assemblies cause lane closures in all directions of the surrounding

b. Lifecycle Cost

Characteristics	Comments
Fabrication steps:	By the choice of process for manufacturing parts, major cost factors are involved.
Parts performance:	The quality and performance of parts, sets the amount of rectification and maintenance that is needed during the constructions design life. These kinds of work are costly, and can be complex in a future urban environment.
Process compatibility:	This factor has a direct effect on cost, although it only occurs during manufacturing.
Material types:	Material type has a direct relation to cost in purchase, processing, recycling or disposal.
Additional experiment:	Minor cost implications during manufacturing.
Matched fastening:	This characteristic has an effect on cost in the long-run, due to the risk of failure and need of maintenance. Depending on technique used, there will be an associated level of complexity when attending it and furthermore cost.

Tolerances:	Tolerance attends to minor deterioration of a construction in a long-term cost perspective. However, it has a vague connection to design life and cost.
Assembly error:	Maintenance and re-work due to assembly error can be a costly issue.
Assembly ease:	Assembly ease only weights the assembly process; it might require some extra expertise or tooling.
Disassembly ease:	Same effect can be said here as with assembly ease, although it can incur during a longer perspective (e.g. maintenance or demolition)
Complex tooling:	Minor effect on the handling and assembly work on-site.
Assembly steps:	Again, this factor has a minor effect on the handling and assembly work on-site.
Threaded fasteners:	This has moderately low effect on cost during joining of parts and need of maintenance.
Guided insertion:	Further increase extra work and therefore cost on-site.

c. Time

<u>**Characteristics**</u>	<u>**Comments**</u>
Combining parts:	Major effect on time spent on-site.
Parts' physiology:	This factor simplify workers situation from having minor confusion, furthermore it can save great deal of time depending on amount of parts, complexity etc.
Stops, notches, guides:	Moderate working error can be avoided.
Axes symmetry:	Mistakes can be avoided with this characteristic, mistake that has minor effect on time.
Surface property:	Depending on the size and parts to be assembled this design characteristic has a moderate effect on time.
Slippery parts:	The effect from this factor, applies in many stages of logistics and construction.
Parts weight:	Heavy parts can complicate handling at site by using machinery and careful procedure.
Tolerances:	On-site preparation might require a small amount of time.
Assembly error:	Depending on the severity and when the error appears it may have a small or major time consumption to re-work or rectify.
Assembly ease:	An initial time can be saved on making the assembly process easier.

Disassembly ease: Saves time by reducing the time spent on internalizing the process and handling the disassembly operations.

Assembly steps: The number of assembly steps adds a minor extra time into each assembly cycle.

Number of fasteners: An extra minor time is needed on each part if many fasteners are used.

Handling and assembly: Standardization can streamline process and routines, therefore give a medium advantage for time.

Assembly process: With unambiguous assembly operations a minor enhancement can be made to the streamlining of the working process on-site.

Assembly direction: Using multiple assembly directions requires organized work in communication, safety measures, handling etc. which all of slows down the assembly process. This creates a medium demand on time spent.

Guided insertion: This adds-on minor time spent on surface finish during assembly.

d. Worker Safety

<u>Characteristics</u> **<u>Comments</u>**

Parts' physiology: The different ways parts can be assembled may trigger mistakes and rework needs which result in exhaustion and mental fatigue in workers

Stops, notches, guides: These kinds of mistakes in design creates minor extra work

Axes symmetry: Minor effect on mistake-proof assembly

Surface property: Properties such as grasp ability directly affect workers handling

Slippery parts: Features as these has a direct dangerous effect on the people handling it

Parts weight: Parts weight creates difficulties in all parts of handling, and also demands heavy and complex machinery which can have life threating risks

Matched fastening: May require minor detail work with smaller tools or machinery

Tolerances: As with previous characteristic, minor additional work can be required.

Assembly error: Not only do assembly errors lead to unplanned rectification works with stressed and weary workers, it is also a direct risk of injuries from construction failure.

Assembly ease: Decreasing insecurity and the need for expertise creates a more comfortable working environment were

	operations can be executed without mistakes and rework. Consequently pressure and risks are reduced.
Disassembly ease:	Disassembly and demolition can require large forces and therefore heavy machineries. In such a situation, there is strong need for making work easy to avoid complex situation involving powerful forces.
Complex tooling:	Delicate handling and tools that are infrequent creates insecurity and stress among worker, leaving them more vulnerable to hazards.
Assembly steps:	Every time a worker shifts between working procedures, a small risk of focus loose or confusion is at hand. With that, risks of mistake or accidents are prone.
Number of fasteners:	The number of fasteners can be a direct cause to extra work to be done in an exposed state where the actual assembly is carried out.
Handling and assembly:	Standardized system enables efficient and organized work on site, which contributes to a clean and safe environment.
Operator learning:	Decreases that short time of insecurity and disordered way of working before operations are learned.
Assembly process:	Ambiguity has an effect on confusion and non-value adding activities, therefore contributing to risk of accidents.
Assembly direction:	Multidirectional assemblies increase the complexity of a worksite, leading to difficulties in organizing work and therefore more prone to accidents and workers fatigue. Also work will have to be executed from high scaffolds or other inconvenient approaches.
Flexible parts:	With this factor, the handling of parts becomes quite difficult. The looseness and misconnection can have a direct effect on workers safety.
Threaded fasteners:	The use of threaded fasteners further increases the extra work required in the frontline of assembly process.
Guided insertion:	Further increases extra work and use of tools in the frontline of assembly.

e. Safety of residents

Characteristics	**Comments**
Complex tooling:	Depending on the size and complexity of the tool or machinery needed a wide range of impact can be incurred, therefore giving this factor a medium weight.
Handling and assembly:	A smooth and standardize routine decrease risks of accidents, with low medium impact on the indicator.

Operator learning: Lower consequence on the hazardous effects set by the work site on residents' safety.

Assembly process: Complex and unambiguous assembly process creates difficult circumstances on the work site which can have a lower medium effect on safety.

f. Noise disturbance

Characteristics	**Comments**
Complex tooling:	The demand of none regular machines and tools usually brings high noise disturbance, therefore giving this factor a medium weight.
Assembly steps:	The amount of assembly steps puts demands on logistics use and different tools, consequently creating sound nuisance. This factor can be considered being a low medium weight.
Number of fasteners:	Since this factor does not only affect the noise from the work-site but also during operation, it will get a medium weight.
Handling and assembly:	This factor can streamline the working process and therefore lower sound levels slightly.
Assembly process:	Non-value adding activities add minor sound emission to the indicator.
Threaded fasteners:	The use of extra tools adds up on the sound emission.
Guided insertion:	Extra surface finish work can create minor noise disturbance.

g. Dust emissions

Characteristics	**Comments**
Combining parts:	This factor can be given a medium weight on the cause of the smaller amount of detail work that is needed to be executed on-site.
Material types:	This is the most important factor when it comes to dust emissions; it sets the possibility to use a non-dust emitting material from the first place.
Parts weight:	The need of heavier machinery has a low medium effect on dust emissions.
Assembly ease:	The reduction of physical work and machinery has a minor effect on dust emissions.
Disassembly ease:	Avoiding demolition and therefore dust emission, an easier disassembly is desired. Demolition has a medium effect on dust emission.
Complex tooling:	The no need for extra non-regular machinery reduces the emission in this indicator.

Assembly steps:	With few assembly steps logistic issues and machinery use can be reduced and therefore dust emissions.
Handling and assembly:	Smother working processes reduce the amount of emissions.
Assembly process:	This factor has a minor effect on dust emissions due to unambiguous assembly process.
Guided insertion:	The need of surface finish work contributes to dust emissions in a minor way.

h. Greenhouse gas

Characteristics	**Comments**
Fabrication steps:	How the fabrication process is set up can have some effect on the emissions of gases, due to its possible variance of impact, it gets a medium weight.
Process compatibility:	With lean production and an effective use of resources, this factor has a medium effect on the indicator.
Combining parts:	Combining parts at site requires extra high energy consuming machinery, therefore giving this factor a low medium weight.
Material types:	Major impact on Greenhouse gases depending on which material is used.
Additional experiment:	Minor effect on emissions if additional experiments are needed.
Parts weight:	Heavy parts require higher need of transportation and therefore the consumption of fuel or energy is high.
Assembly ease:	The machinery on-site has high GHG emissions, therefore if higher effort is needed the use of machinery is increased and further the total emissions.
Disassembly ease:	Similar analogy here as for assembly eases.
Handling and assembly:	Standardizing and smooth lining the working process has a minor effect on the contribution to gas emissions.
Guided insertion:	Additional surface finish work adds minor emissions to this indicator.

i. Energy use

Characteristics	**Comments**
Fabrication steps:	How the fabrication process is set up can have some effect on energy use, due to its possible variance of impact, it gets a medium weight.
Process compatibility:	With lean production and an effective use of resources, this factor has a medium effect on the indicator.

Combining parts:	Combining parts at site requires extra high energy consuming machinery, therefore giving this factor a low medium weight.
Material types:	Major impact on the consumption of energy depending on which material is used.
Additional experiment:	Minor effect on energy use if additional experiments are needed.
Assembly ease:	The machinery on-site has high energy consumption, therefore if higher effort is needed the use of machinery is increased and further the energy use.
Disassembly ease:	Similar analogy here as for assembly eases.
Complex tooling:	Machinery of higher energy consumption might be used if this factor comes into play, giving a minor contribution to the indicator.
Assembly steps:	Energy waste is reduced if the amount of activities is shortened.
Handling and assembly:	Standardizing and smooth lining the working process has a minor effect on the contribution to energy consumption.
Guided insertion:	Additional surface finish work adds minor consumption to this indicator.

j. Waste reduction/recycling

<u>Characteristics</u>	<u>Comments</u>
Fabrication steps:	Since the fabrication environment is more controlled and allows better waste control, it does not have any major effect on the indicator.
Parts performance:	High quality parts are less susceptible to damage and may even be reused after disassembly, therefore giving this factor a medium weight.
Process compatibility:	Similar with fabrication steps, waste is not of a big issue when concerning industry environment.
Combining parts:	This factor has an impact on the work on-site and the risk and delicateness of many small parts is not as prevalent anymore.
Material types:	The material used determines possibilities of recycling or making the part less susceptible to waste.
Assembly error:	The errors on-site during assembly are of major cause for waste production. However, there are a wide range of assembly errors, therefore assigning this factor medium weight.

APPENDIX B:
EVALUATION TABLES

EVALUATION CHART

Technical Concept 1: Snap-fit connection between FRP deck and steel girders

General DFMA Criteria	Manufacturing Characteristics	Mobility		LCC		Time		Worker safety		Safety of residents		Noise disturbance		Dust emission		GHG		Energy use		Waste reduction	
		Weight	Score	***Weight***	Score	***Weight***	Score	***Weight***	Score	***Weight***	Score	***Weight***	Score	***Weight***	Score	***Weight***	Score	***Weight***	Score	***Weight***	Score
Simplified design for manufacturing	Fabrication steps			***5***	-											***3***	-	***3***	-	***1***	-
	Parts performance			***5***	-															***3***	3
	Process compatibility			***2***	-											***3***	-	***3***	-	***1***	-
Parts number	Combining parts					***5***	5							***3***	3	***2***	2	***2***	2	***2***	2
Common parts and materials	Material types			***5***	0									***5***	5	***5***	-	***5***	-	***5***	0
	Additional experiment			***1***	-											***1***	-	***1***	-		
Mistake-proof product design	Parts' physiology					***2***	0	***3***	0												
	Stops, notches, guides					***1***	0	***1***	1												
	Axes symmetry					***1***	1	***1***	1												
Ease of parts orientation handling and assembly	Surface property	***2***	0			***2***	0	***4***	4												
	Sticky and slippery parts					***3***	0	***5***	5												
	Parts weight	***5***	5			***3***	3	***5***	5					***2***	2	***3***	3				
Efficient joining	Matched fastening			***4***	0			***1***	1												
Surface finishing	Tolerances			***2***	2	***1***	1	***1***	1												
Total Score (Manufacturing)			***5***		***2***		***10***		***18***		***0***		***0***		***10***		***5***		***2***		***5***
Max Possible (Manufacturing)			***7***		***11***		***18***		***21***		***0***		***0***		***10***		***5***		***2***		***10***

General DFMA Criteria	Assembly Characteristics	Mobility		LCC		Time		Worker safety		Safety of residents		Noise disturbance		Dust emission		GHG		Energy use		Waste reduction	
		Weight	Score	*Weight*	Score	*Weight*	Score	*Weight*	Score	*Weight*	Score	*Weight*	Score	*Weight*	Score	*Weight*	Score	*Weight*	Score	*Weight*	Score
Simplified design for assembly	Assembly error	*5*	0	*3*	3	*3*	3	*5*	5											*3*	3
	Assembly ease			*1*	1	*2*	2	*3*	3					*1*	1	*2*	2	*2*	2		
	Disassembly ease			*2*	0	*1*	0	*4*	0					*3*	0	*2*	0	*2*	0		
	Complex tooling	*4*	4	*1*	1			*2*	2	*3*	3	*3*	3	*2*	2			*1*	1		
Reduced number of parts	Assembly steps	*4*	4	*1*	1	*1*	1	*1*	1			*2*	2	*2*	2			*1*	1		
	Number of fasteners	*3*	0			*1*	1	*1*	1			*3*	0								
Common parts and materials	Handling and assembly	*2*	2			*2*	2	*3*	3	*2*	2	*1*	1	*1*	1	*1*	1	*1*	1		
	Operator learning							*1*	1	*1*	1										
Mistake-proofings	Assembly process	*1*	1			*1*	1	*1*	1	*2*	2	*1*	1	*1*	1						
Parts orientation	Assembly direction	*5*	5			*3*	3	*4*	4												
	Flexible and flimsy parts							*4*	4												
Efficient joining	Threaded fasteners			*2*	2			*1*	1			*1*	1								
Surface finishing	Guided insertion			*1*	1	*1*	1	*2*	2			*1*	1	*1*	1	*1*	1	*1*	1		
Total Score (Assembly)			***16***		***9***		***14***		***28***		***8***		***9***		***8***		***4***		***6***		***3***
Maximum Possible (Assembly)			***24***		***11***		***15***		***32***		***8***		***12***		***11***		***6***		***8***		***3***
Grand Total Score			***21***		***11***		***24***		***46***		***8***		***9***		***18***		***9***		***8***		***8***
Grand Maximum Possible			***31***		***22***		***33***		***53***		***8***		***12***		***21***		***11***		***10***		***13***

EVALUATION CHART

Technical Concept 2: Bolted connection between FRP deck and steel girders

General DFMA Criteria	Manufacturing Characteristics	Mobility		LCC		Time		Worker safety		Safety of residents		Noise disturbance		Dust emission		GHG		Energy use		Waste reduction	
		Weight	Score	***Weight***	Score	***Weight***	Score	***Weight***	Score	***Weight***	Score	***Weight***	Score	***Weight***	Score	***Weight***	Score	***Weight***	Score	***Weight***	Score
Simplified design for manufacturing	Fabrication steps			***5***	-											***3***	-	***3***	-	***1***	-
	Parts performance			***5***	-															***3***	3
	Process compatibility			***2***	-											***3***	-	***3***	-	***1***	-
Parts number	Combining parts					***5***	5							***3***	3	***2***	2	***2***	2	***2***	2
Common parts and materials	Material types			***5***	0									***5***	5	***5***	-	***5***	-	***5***	0
	Additional experiment			***1***	-											***1***	-	***1***	-		
Mistake-proof product design	Parts' physiology					***2***	0	***3***	0												
	Stops, notches, guides					***1***	0	***1***	0												
	Axes symmetry					***1***	1	***1***	1												
Ease of parts orientation handling and assembly	Surface property	***2***	0			***2***	0	***4***	0												
	Sticky and slippery parts					***3***	0	***5***	5												
	Parts weight	***5***	5			***3***	3	***5***	5					***2***	2	***3***	3				
Efficient joining	Matched fastening			***4***	0			***1***	1												
Surface finishing	Tolerances			***2***	2	***1***	1	***1***	1												
Total Score (Manufacturing)			***5***		***2***		***10***		***13***		***0***		***0***		***10***		***5***		***2***		***5***
Max Possible (Manufacturing)			***7***		***24***		***18***		***21***		***0***		***0***		***10***		***17***		***14***		***12***

General DFMA Criteria	Assembly Characteristics	Mobility		LCC		Time		Worker safety		Safety of residents		Noise disturbance		Dust emission		GHG		Energy use		Waste reduction	
		Weight	Score	***Weight***	Score	***Weight***	Score	***Weight***	Score	***Weight***	Score	***Weight***	Score	***Weight***	Score	***Weight***	Score	***Weight***	Score	***Weight***	Score
Simplified design for assembly	Assembly error	***5***	5	***3***	3	***3***	3	***5***	5											***3***	3
	Assembly ease			***1***	1	***2***	2	***3***	3					***1***	1	***2***	2	***2***	2		
	Disassembly ease			***2***	2	***1***	1	***4***	4					***3***	3	***2***	2	***2***	2		
	Complex tooling	***4***	4	***1***	1			***2***	2	***3***	3	***3***	3	***2***	2			***1***	1		
Reduced number of parts	Assembly steps	***4***	0	***1***	1	***1***	1	***1***	1			***2***	2	***2***	2			***1***	1		
	Number of fasteners	***3***	3			***1***	1	***1***	1			***3***	3								
Common parts and materials	Handling and assembly	***2***	2			***2***	2	***3***	3	***2***	2	***1***	1	***1***	1	***1***	1	***1***	1		
	Operator learning							***1***	1	***1***	1										
Mistake-proofings	Assembly process	***1***	1			***1***	1	***1***	1	***2***	2	***1***	1	***1***	1						
Parts orientation	Assembly direction	***5***	5			***3***	3	***4***	4												
	Flexible and flimsy parts							***4***	4												
Efficient joining	Threaded fasteners			***2***	0			***1***	0			***1***	0								
Surface finishing	Guided insertion			***1***	1	***1***	1	***2***	2			***1***	1	***1***	1	***1***	1	***1***	1		
Total Score (Assembly)			***20***		***9***		***15***		***31***		***8***		***11***		***11***		***6***		***8***		***3***
Maximum Possible (Assembly)			***24***		***11***		***15***		***32***		***8***		***12***		***11***		***6***		***8***		***3***
Grand Total Score			***25***		***11***		***25***		***44***		***8***		***11***		***21***		***11***		***10***		***8***
Grand Maximum Possible			***31***		***35***		***33***		***53***		***8***		***12***		***21***		***23***		***22***		***15***

EVALUATION CHART

Technical Concept 3: Shear-stud connection between FRP deck and steel girders

General DFMA Criteria	Manufacturing Characteristics	Mobility		LCC		Time		Worker safety		Safety of residents		Noise disturbance		Dust emission		GHG		Energy use		Waste reduction	
		Weight	Score	*Weight*	Score	*Weight*	Score	*Weight*	Score	*Weight*	Score	*Weight*	Score	*Weight*	Score	*Weight*	Score	*Weight*	Score	*Weight*	Score
Simplified design for manufacturing	Fabrication steps			5	-											3	-	3	-	1	-
	Parts performance			5	-															3	3
	Process compatibility			2	-											3	-	3	-	1	-
Parts number	Combining parts					5	5							3	3	2	2	2	2	2	2
Common parts and materials	Material types			5	0									5	5	5	-	5	-	5	0
	Additional experiment			1	-											1	-	1	-		
Mistake-proof product design	Parts' physiology					2	0	3	0												
	Stops, notches, guides					1	0	1	0												
	Axes symmetry					1	0	1	1												
Ease of parts orientation handling and assembly	Surface property	2	0			2	0	4	0												
	Sticky and slippery parts					3	0	5	5												
	Parts weight	5	0			3	0	5	0					2	0	3	0				
Efficient joining	Matched fastening			4	0			1	1												
Surface finishing	Tolerances			2	0	1	0	1	0												
Total Score (Manufacturing)			***0***		***0***		***5***		***7***		***0***		***0***		***8***		***2***		***2***		***5***
Max Possible (Manufacturing)			***7***		***24***		***18***		***21***		***0***		***0***		***10***		***17***		***14***		***12***

General DFMA Criteria	Assembly Characteristics	Mobility		LCC		Time		Worker safety		Safety of residents		Noise disturbance		Dust emission		GHG		Energy use		Waste reduction	
		Weight	Score	***Weight***	Score	***Weight***	Score	***Weight***	Score	***Weight***	Score	***Weight***	Score	***Weight***	Score	***Weight***	Score	***Weight***	Score	***Weight***	Score
Simplified design for assembly	Assembly error	***5***	5	***3***	3	***3***	3	***5***	5											***3***	3
	Assembly ease			***1***	1	***2***	2	***3***	3					***1***	1	***2***	0	***2***	0		
	Disassembly ease			***2***	2	***1***	0	***4***	0					***3***	0	***2***	0	***2***	0		
	Complex tooling	***4***	0	***1***	0			***2***	2	***3***	0	***3***	0	***2***	0			***1***	1		
Reduced number of parts	Assembly steps	***4***	4	***1***	1	***1***	1	***1***	1			***2***	2	***2***	2			***1***	1		
	Number of fasteners	***3***	0			***1***	1	***1***	1			***3***	3								
Common parts and materials	Handling and assembly	***2***	2			***2***	2	***3***	3	***2***	2	***1***	1	***1***	1	***1***	1	***1***	1		
	Operator learning							***1***	1	***1***	1										
Mistake-proofings	Assembly process	***1***	1			***1***	1	***1***	1	***2***	2	***1***	1	***1***	1						
Parts orientation	Assembly direction	***5***	0			***3***	0	***4***	0												
	Flexible and flimsy parts							***4***	4												
Efficient joining	Threaded fasteners			***2***	2			***1***	1			***1***	1								
Surface finishing	Guided insertion			***1***	0	***1***	0	***2***	0			***1***	0	***1***	0	***1***	0	***1***	0		
Total Score (Assembly)			***12***		***9***		***10***		***22***		***5***		***8***		***5***		***1***		***3***		***3***
Maximum Possible (Assembly)			***24***		***11***		***15***		***32***		***8***		***12***		***11***		***6***		***8***		***3***
Grand Total Score			***12***		***9***		***15***		***29***		***5***		***8***		***13***		***3***		***5***		***8***
Grand Maximum Possible			***31***		***35***		***33***		***53***		***8***		***12***		***21***		***23***		***22***		***15***

EVALUATION CHART

Technical Concept 4: Bar-and-slot and snap-fit connections between FRP deck panels

General DFMA Criteria	Manufacturing Characteristics	Mobility		LCC		Time		Worker safety		Safety of residents		Noise disturbance		Dust emission		GHG		Energy use		Waste reduction	
		Weight	Score	***Weight***	Score	***Weight***	Score	***Weight***	Score	***Weight***	Score	***Weight***	Score	***Weight***	Score	***Weight***	Score	***Weight***	Score	***Weight***	Score
Simplified design for manufacturing	Fabrication steps			***5***	-											***3***	-	***3***	-	***1***	-
	Parts performance			***5***	-															***3***	3
	Process compatibility			***2***	-											***3***	-	***3***	-	***1***	-
Parts number	Combining parts					***5***	5							***3***	3	***2***	2	***2***	2	***2***	2
Common parts and materials	Material types			***5***	0									***5***	5	***5***	-	***5***	-	***5***	0
	Additional experiment			***1***	-											***1***	-	***1***	-		
Mistake-proof product design	Parts' physiology					***2***	2	***3***	0												
	Stops, notches, guides					***1***	0	***1***	0												
	Axes symmetry					***1***	1	***1***	1												
Ease of parts orientation handling and assembly	Surface property	***2***	0			***2***	0	***4***	0												
	Sticky and slippery parts					***3***	3	***5***	5												
	Parts weight	***5***	5			***3***	3	***5***	5					***2***	2	***3***	3				
Efficient joining	Matched fastening			***4***	4			***1***	1												
Surface finishing	Tolerances			***2***	2	***1***	1	***1***	1												
Total Score (Manufacturing)			***5***		***6***		***15***		***13***		***0***		***0***		***10***		***5***		***2***		***5***
Max Possible (Manufacturing)			***7***		***24***		***18***		***21***		***0***		***0***		***10***		***17***		***14***		***12***

General DFMA Criteria	Assembly Characteristics	Mobility		LCC		Time		Worker safety		Safety of residents		Noise disturbance		Dust emission		GHG		Energy use		Waste reduction	
		Weight	Score	***Weight***	Score	***Weight***	Score	***Weight***	Score	***Weight***	Score	***Weight***	Score	***Weight***	Score	***Weight***	Score	***Weight***	Score	***Weight***	Score
Simplified design for assembly	Assembly error	***5***	5	***3***	3	***3***	3	***5***	5											***3***	3
	Assembly ease			***1***	1	***2***	2	***3***	3					***1***	1	***2***	2	***2***	2		
	Disassembly ease			***2***	2	***1***	1	***4***	4					***3***	3	***2***	2	***2***	2		
	Complex tooling	***4***	4	***1***	1			***2***	2	***3***	3	***3***	3	***2***	2			***1***	1		
Reduced number of parts	Assembly steps	***4***	4	***1***	1	***1***	1	***1***	1			***2***	2	***2***	2			***1***	1		
	Number of fasteners	***3***	3			***1***	1	***1***	1			***3***	3								
Common parts and materials	Handling and assembly	***2***	2			***2***	2	***3***	3	***2***	2	***1***	1	***1***	1	***1***	1	***1***	1		
	Operator learning							***1***	1	***1***	1										
Mistake-proofings	Assembly process	***1***	1			***1***	1	***1***	1	***2***	2	***1***	1	***1***	1						
Parts orientation	Assembly direction	***5***	5			***3***	3	***4***	4												
	Flexible and flimsy parts							***4***	4												
Efficient joining	Threaded fasteners			***2***	2			***1***	1			***1***	1								
Surface finishing	Guided insertion			***1***	1	***1***	1	***2***	2			***1***	1	***1***	1	***1***	1	***1***	1		
Total Score (Assembly)			***24***		***11***		***15***		***32***		***8***		***12***		***11***		***6***		***8***		***3***
Maximum Possible (Assembly)			***24***		***11***		***15***		***32***		***8***		***12***		***11***		***6***		***8***		***3***
Grand Total Score			***29***		***17***		***30***		***45***		***8***		***12***		***21***		***11***		***10***		***8***
Grand Maximum Possible			***31***		***35***		***33***		***53***		***8***		***12***		***21***		***23***		***22***		***15***

EVALUATION CHART

CONXL

General DFMA Criteria	Manufacturing Characteristics	Mobility		LCC		Time		Worker safety		Safety of residents		Noise disturbance		Dust emission		GHG		Energy use		Waste reduction	
		Weight	Score	***Weight***	Score	***Weight***	Score	***Weight***	Score	***Weight***	Score	***Weight***	Score	***Weight***	Score	***Weight***	Score	***Weight***	Score	***Weight***	Score
Simplified design for manufacturing	Fabrication steps			***5***	-											***3***	-	***3***	-	***1***	-
	Parts performance			***5***	5															***3***	3
	Process compatibility			***2***	-											***3***	-	***3***	-	***1***	-
Parts number	Combining parts					***5***	5							***3***	0	***2***	0	***2***	0	***2***	0
Common parts and materials	Material types			***5***	0									***5***	5	***5***	5	***5***	5	***5***	5
	Additional experiment			***1***	-											***1***	-	***1***	-		
Mistake-proof product design	Parts' physiology					***2***	2	***3***	0												
	Stops, notches, guides					***1***	0	***1***	1												
	Axes symmetry					***1***	1	***1***	1												
Ease of parts orientation handling and assembly	Surface property	***2***	2			***2***	0	***4***	4												
	Sticky and slippery parts					***3***	3	***5***	5												
	Parts weight	***5***	0			***3***	3	***5***	0					***2***	0	***3***	0				
Efficient joining	Matched fastening			***4***	4			***1***	1												
Surface finishing	Tolerances			***2***	2	***1***	1	***1***	1												
Total Score (Manufacturing)			***2***		***11***		***15***		***13***		***0***		***0***		***5***		***5***		***5***		***8***
Max Possible (Manufacturing)			***7***		***24***		***18***		***21***		***0***		***0***		***10***		***17***		***14***		***12***