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EXTENDING ORIGAMI TECHNIQUE TO FOLD FORMING OF SHEET METAL PRODUCTS

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EXTENDING ORIGAMI TECHNIQUE TO FOLD
FORMING OF SHEET METAL PRODUCTS

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ABSTRACT

This dissertation presents a scientific based approach for the analysis of folded sheet metal products. Such analysis initializes the examination in terms of topological exploration using set of graph modeling and traversal algorithms. The geometrical validity and optimization are followed by utilizing boundary representation and overlapping detection during a geometrical analysis stage, in this phase the optimization metrics are established to evaluate the unfolded sheet metal design in terms of its manufacturability and cost parameters, such as nesting efficiency, total welding cost, bend lines orientation, and maximum part extent, which aides in handling purposes.

The proposed approach evaluates the design in terms of the stressed-based behavior to indicate initial stress performance by utilizing a structural matrix analysis while developing modification factors for the stiffness matrix to cope with the stress-based differences of the diverse flat pattern designs. The outcome from the stressed-based ranking study is mainly the axial stresses as exerted on each element of folded geometry; this knowledge leads to initial optimizing the flat pattern in terms of its stress-based behavior. Furthermore, the sheet folding can also find application in composites manufacturing. Thus, this dissertation optimizes fiber orientation based on the elasticity theory principles, and the best fiber alignment for a flat pattern is determined under certain stresses along with the peel shear on adhesively bonded edges.

This study also explores the implementation of the fold forming process within the automotive production lines. This is done using a tool that adopts Quality Function

Deployment (QFD) principle and Analytical Hierarchy Process (AHP) methodology to structure the reasoning logic for design decisions. Moreover, the proposed tool accumulates all the knowledge for specific production line and parts design inside an interactive knowledge base. Thus, the system is knowledge-based oriented and exhibits the ability to address design problems as changes occur to the product or the manufacturing process options. Additionally, this technique offers two knowledge bases; the first holds the production requirements and their correlations to essential process attributes, while the second contains available manufacturing processes options and their characteristics to satisfy the needs to fabricate Body in White (BiW) panels. Lastly, the dissertation showcases the developed tools and mathematics using several case studies to verify the developed system's functionality and merits. The results demonstrate the feasibility of the developed methodology in designing sheet metal products via folding.

DEDICATION

I lovingly dedicate this dissertation to my wonderful family, who supported me through each step of the way. Particularly, to my understanding and loving husband, Mahmoud, for his endless support and patience, and to my baby-to-be, who filled our life with joy and excitement.

I also dedicate this work to my great parents, Abdel Lateif and Amira, who provided me with endless support and encouragement during my whole life, and to my siblings, Shimaa, Essraa, Ibrahim, Zahraa, and Ali, for their boundless friendship and delightful encouragement. I would also thank my best friend, Dima Alsbeih, for all the help she offered during my early preparation for graduate school.

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CHAPTER ONE

INTRODUCTION

1.1   Motivation

Sheet metal fold forming can be used to consolidate parts and form the structural

part of any system or mechanical design such as vehicular Body in White panels (BiW) -

panels. However, fold forming can best be implemented using metals by creating a set of

material discontinuities along the bend line, to facilitate the bending and the shaping of

the final geometry. The 2- dimensional (2-D) flat strip can be designed to have multiple

folds to yield intricate 3–dimensional (3-D) shapes, using lesser number of panels and

subsequently requiring lesser joining and processing, when compared with from the

current press-based forming of automobile body structures.

The fold forming performance is anticipated to overcome some of the challenges

faced in press-based stamping (Vijayakumar 2010), when analyzed based on several

desired attributes mainly; the ability of the process to reduce the number of components

and lead time while utilizing a common platform, to enable modularity and

standardization between different vehicle models. Press-based stamping is considered a

complex process (Omar et al. 2008), due to the multitude of parameters that need to be

controlled; such as the part shape and the different forming modes, the forming operation

in terms of tonnage control, the uniformity of material properties; in addition to the

variety of material types and grades. Silva et al. (2003) stated that at least 40 variables could affect the stamping process quality.

In addition, the stamping process includes high tooling cost for the die design and validation, which can consume around 52 weeks of the development effort at around $4 to $5 million in design cost per die; whereas, fold forming requires minimal tooling, because it applies a series of blanking and punching operations to create discontinuities along the bend line. Also such features can be created using a laser-cutting machine, which achieves a higher accuracy at greater flexibility. The lack of rigid tooling in fold forming enables it to offer greater flexibility in the process sequence and the material flow; in reality it enables an actual one-piece flow production. Also fold forming can reduce the secondary joining operations, when compared to the multiple welding lines needed for the discrete stamped parts.

Additional advantages of the fold forming come from the fact that the discontinuities at the bend lines affect the bending force and remove the limitations on bending radius; consequently controls the occurrence of tears and cracks. Moreover, the creation of material discontinuities along the bend line can reduce the punch displacement analysis that is needed in traditional bending. Kalpakjian et al. (2006) described the use of material's discontinuities at the bend line as a mean to control the bending defects in flanges and to obtain bends with sharp radii.

In spite of the aforementioned discussion and the fold forming potentials, this technology from the design and analysis point of views is not yet well established based a scientific approach. The discussion in following sections will propose a possible

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approach to analyze and help design fold formed shapes for sheet metal applications using computational geometry mathematics.

1.2   Problem Statement

The problem of "unfolding" is concerned with the transformation of one geometry from a 3-Dimensional (3-D) state or world to the 2- Dimensional (2-D) layout, which is referred to in this work as flat pattern, by an act of unfolding or unrolling with the condition that any generated flat pattern is not self-intersecting; Self-intersecting flat patterns are the unfolded 3-D layouts that are not feasible to be folded again due to surfaces overlapping; i.e. cannot be cut out of 2-D metal sheet and folded though it is topologically valid. This challenge is commonly encountered in Origami, the most famous application of paper unfolding, and in many industries and applications as packaging using carton, packaging for cloth sheets, and metal sheet fold forming.

The published research that is dedicated to folding papers into Origami structures is neither readily usable nor sufficient to be applied to sheet metal folding. This is due to the differences between the 3-D hollow folded objects (with zero thickness i.e. paper) and the flat folded sheet metal structures, specifically in terms of the geometrical and the topological constraints. Moreover, the mechanical requirements in a sheet metal product add further constraints that do not exist for paper folding.

There is a lack of the tools and/or procedures to analyze folded sheet metal products in terms of its topological, geometrical and stress-based aspects that can better reflect the designed product final proprieties; with respect to its manufacturability and cost requirements. Additionally, no standardized procedures exist to help evaluate folded

geometries in terms of its stressed-based performance under certain loading schemes, and help investigate the extension of fold forming into composite structures manufacturing and design.

1.3 Objectives

From the above discussion, there is a need to develop a scientific based set of procedures to address folded sheet metal products design. Such approach will aid the process objectively evaluating products design in terms of topological, geometrical and stress-based aspects. The goal of this dissertation is to develop such scientific rule-based approach and provide an assessment tool for designers when dealing with sheet metal folding products. The proposed approach can be described in the following main steps or phases;

Firstly, the topological analysis phase determines the possible flat patterns that can be potentially folded to form the desired 3-D shape. This analysis depends on the connectivity arrangement of the part and it helps the designer in predicting the nesting arrangement and welding characteristics (such as weld lines location), length of welded edges, and the total cost of welding or joining. This phase will also offer an optimization tool to select the design with the least cost and the best manufacturability scores.

Secondly, the geometrical analysis step will investigate which flat patterns comply with the geometrical restrictions as the non-overlapping faces criteria. It also eliminates the impracticable designs of sheet metal parts during the early stages of the analysis. Furthermore in this step, the design of the flat patterns can be optimized in terms of the geometrical aspect.

Thirdly, the stress-based analysis will help in defining the final stress-based of the designed folded part and will provide the feedback (in terms of design changes) needed to adjust parts' design in terms of the candidate flat pattern. Furthermore, since the sheet folding can also find application in composites manufacturing, the dissertation aims at providing an optimization indices for flat pattern design with respect to composite material's properties, such as fiber orientation and the effect of peel shear on adhesively bonded edges.

Lastly, the analysis will investigate the implementation of the fold forming process in current production lines against the process and product requirements and attributes. This will be done using decision-making tools programmed into a KBS to provide the flexibility in conducting analysis while considering previously gained experience.

1.4   Approaches

The first step in the developed system is to model and study the folded structures using graph theory and traversal algorithms; this enables the system to conduct topological analysis for the components' connectivity without the need to consider its actual geometry. Afterward, optimization metrics are developed to rate the resulted designs as flat pattern design. Then a set of geometrical analysis techniques is utilized as B-rep and overlapping detection to judge the validity of topological results.

Subsequently, the stressed-based examination is performed using structural matrix analysis via a specific modification procedure for the stiffness matrix of each of the flat

pattern characteristics; this step enables the stressed-based evaluation to distinguish between the various designs of unfolded geometries.

The composite material application is addressed later in the dissertation, since the application of Origami-based folded objects for different materials has a great potential especially with the merits that composites have in engineering applications. This chapter application highlights the future expansion for Origami-based folding for composite materials and clarifies other dimension for the study of flat pattern design. In this work the effect of the fiber arrangement on the final mechanical properties of a folded composite structure is investigated using the elasticity theory. A model is constructed to examine the best fiber orientation under certain directional stresses, and then peel shear analysis is implemented to reveal the effect of the adhesively bonded edges in combination with the flat pattern design that best serve the optimum adhesively bonded edge combination.

The last part of the dissertation work discusses the development of a combined Quality Function Deployment (QFD) and Analytical Hierarchy Processes (AHP) approaches to evaluate the fold folding process relative to a user defined production requirements in addition to the traditional manufacturing processes involved in forming the Body in White BiW panels, this combined approach is further packaged using a Knowledge-Based System (KBS) and complemented with graphical user interface on a web-based platform.

CHAPTER TWO

THE FLAT PATTERN ANALYSIS

2.1   Introduction

In the sheet metal folding process, metallic products are formed by multiple sequential bending processes; while, in traditional metal sheet forming (stamping), the various components of a part are formed mainly by stamping the shapes by means of a press and a die, which is followed by a sequence of assembling processes that are utilized to join the product's components together by means of welding and riveting. Some features in one part can be shaped by pure bending; however this is not an efficient procedure to form most of the part features as a result of hard tooling accessibility, limitations on bending radii, defects that may occur in material as cracks and tears, springback, limitations on the direction of bending relative to the rolling direction (anisotropy effects), the need for accurate calculation to locate bending line, and the punch displacement calculations.

Sheet metal fold forming can be used to consolidate all components of a product. Yet, fold forming can best be implemented by creating a set of material discontinuities along a bend line; to facilitate the bending and the shaping of the final geometry. These material discontinuities allow the part to be folded from one piece of sheet metal, compared to the multiple welding and riveting steps required in traditional sheet metal parts. As a result, the 2- dimensional (2-D) flat strip can be subjected to multiple folds to

create the intricate 3–dimensional (3-D) shapes using lesser number of individually shaped metal parts. The conventional use of material discontinuities in bending is intended to control the defects in flanges or to achieve sharp bending radii (Kalpakjian et al. 2006). Figure 2.1 shows folded sheet metal part with material discontinuities with produced along the bend line by Industrial Origami ® Company.

(a)

(b)

(c)

(d)
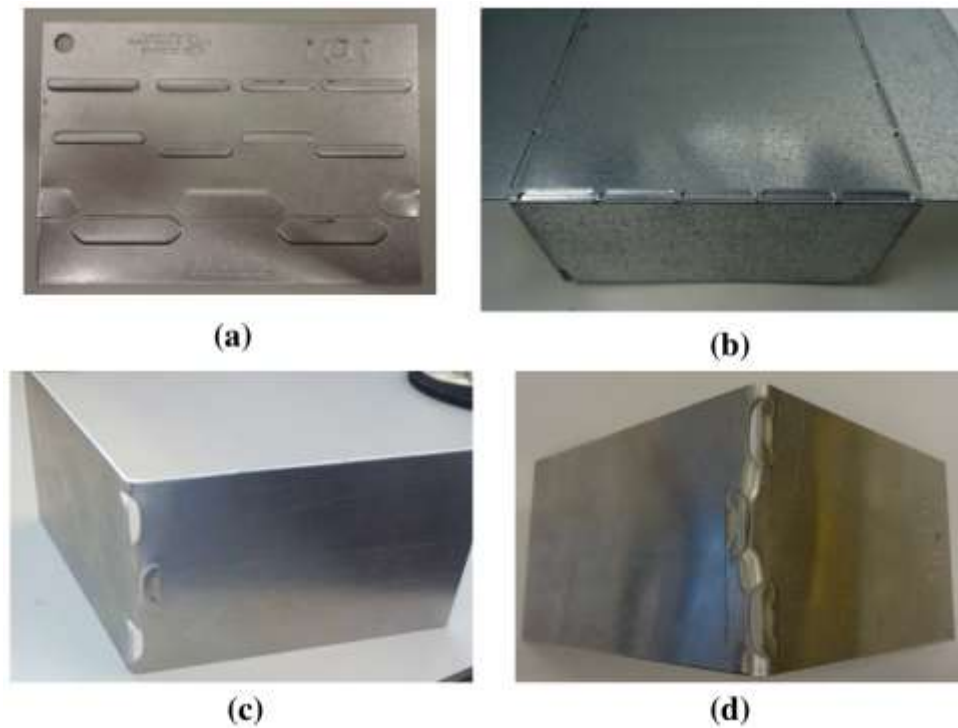
Figure 2.1 Folded sheet metal products with material discontinuities along the bend line by Industrial Origami® (a) Several types of stamped features. (b) Open box structure with stamped features along bend line. (c) – (d) Bend line determined by laser cut features.

The design process of folded sheet metal parts goes through the stages of rough sketching, 3-D reconstruction, flat pattern analysis, geometrical modification, accurate model generation, and the testing of the final part by simulation. (Shpitalni et al. 2000).

The flat pattern analysis phase studies the 2-D footprint of the part to be folded into 3-D; because the topological analysis of a sheet metal part generates multiple 2-D patterns that all can be successfully folded to the final desired geometry. This fact necessitates selection criteria to favorably decide on a 2-D flat pattern that accounts for economic considerations, process requirements and efficiency.

2.2   Related Work

The study of folded objects goes back to the science of paper origami, where a thin-walled sheet is bended multiple times to generate a flat or a piecewise flat structure. Researchers developed mathematical models to examine the properties of Origami. Hull (1994 and 1996) discussed the properties of Origami models and the sufficient conditions to locally flat fold a structure. While Bern et al. (1996) studied models for crease patterns that can be flat folded. Lang (1996) considered a computational algorithm to generate patterns to be folded into various Origami shapes. On the other hand, Lee et al. (1996) investigated the different mechanisms of paper folded structures, his research developed simulation and modeling parameters for pop-up boxes. However, most of these studies focused on the shape and the motion rather than the topology. Dai et al. (1999) analyzed the mechanisms that change the structure upon folding. The automation of the folding process have also been under analysis as well; Elsayed et al. (2004) proposed a novel approach for the continuous folding process of sheet materials by a set of rollers, which can produce the desired folded patterns as in impact energy absorption pads. His work presented a folding machine design for producing such pads.

The published research that is dedicated to folding papers into Origami structures is neither readily usable nor sufficient to be applied to sheet metal products. This fact is due to the differences between the 3-D hollow folded objects (with zero thickness i.e. papers) and the flat folded sheet metal structures; specifically in terms of the geometrical and the topological constraints.

The folding problem generally faced in packaging industry, where the material's characteristics are more approximated to paper such as carton sheets packaging materials. Dai (1996) presented the folding of cardboards for packaging, where the design was set based on the machines capabilities to a familiar geometry selected by the designer's experience. Automated machines were dedicated to one type of cartons; hence the system could not handle any change in the geometry or shape of the carton without extensive improvements to the folding machines. While, simpler geometries were handled by Lu et al. (2000), the authors reported a folding mechanism with fixtures by generating all possible folding sequences by analyzing the possible motions for a carton, however, the approach dealt with simple rectangular geometries, and did not count for all possibilities of 2-D footprints to fold it to the desired 3-D final shape.

Other techniques focused on specific geometries, where a predetermined 2-D layout is specified by the designer as in the work of Dai el al. (2002), the authors investigated carton packaging by presenting a mathematical approach to specify the mobility of specific geometries of carton products by applying line vectors and screw theory in combination with graph representation to investigate the mobility and the carton manipulation during the folding processes, however the geometries are limited

and predefined. Designing packaging shapes based on motion planning and configuration transformation were studied by Liu and Dai (2002) as well; they discussed the folding process of packaging cartons through modeling the folding problem into a metamorphic mechanism, where the carton creases were represented as joints connecting the carton panels. The authors used graph representation in order to identify the actuating joints followed by graph decomposition to determine the folding sequence; their work investigated the motion trajectory for carton products, however the approach did not investigate all possible folding sequences, the effect on the final part design, or the various forms to fold a 3-D shape.

Other approaches focused on the type of tooling to fold a packaging material in order to explore the design, Liu and Dai (2003) used hypothetical mechanism and trajectory for carton folds motion in combination with dual robotic fingers to perform the folding, hence their work estimated the trajectory of each fold and kinematical modeling for the robotic fingers. On the other hand, Dubey and Dai (2006) handled the folding problem for complex geometries and shapes used in carton packaging, the authors approach was to categorize the type of folded carton product based on its geometry in order to determine the type of machine needed to perform the folding, hence they studied the design of reconfigurable machine that can handle folding complex geometries. However, their analysis did not consider the various forms a flat pattern of a carton can be design, hence the folding sequence governed only the order of folding the fold lines and not the possible location of fold lines in a 3-D folded.

Consequently, the packaging industry utilizes tools that depend on:

- Determining the folding machine capability.

- Determining the folding sequence.

- Determining the mobility of specific geometries (mathematical approach and screw theory application).

- Modeling folding objects as metamorphic mechanisms.

- Combining folding mechanisms and trajectory with robotics effector specification. (It is another approach depends on folding machine capabilities).

However, the approaches either handled simple geometries or tackled specific and limited known geometries. In addition, no exploration for all possible 2-D designs can be conducted when using any of the listed techniques above; rather the initial flat pattern depends on designer's experience and knowledge of the machinery capabilities. Afterwards, the design can be modified according to the technique used but there is no guarantee that the resulted output is the optimum one. Moreover, none of the approaches followed are generic in nature, rather most are dependent on the type of machinery or geometries under manufacturing and hence the tools followed cannot be explicitly used for the design of folding objects.

In traditional manufacturing approach, where the bending operation of sheet metal products is carried via sets of dies and punches, the design of flat pattern or a 2-D foot print of the desired product heavily depends on the designer expertise and creativity. Current practice of sheet metal part design typically proceeds as follows; the designer interprets the functional and geometric constraints for a part in CAD environment, then

he/she creates a form representation using suitable geometric identities such as line types, group and layer information. Lastly, he draws a wireframe model that is passed to the manufacturing engineer, who reads the 3-D wireframe model and unfold it, then he adds material data and adjusts it according to bend allowance. Finally, he checks the results and resolves manufacturing issues by hand (Wang et al. 1996).

Efforts to analyze and automate the process of flat pattern generation for traditional fabrication methods of metallic sheets focused on two orientations, the first is based on feature recognition and extraction, the second is based on expert systems generation to substitute designers expertise and knowledge. Both approaches served as inputs to a process planning tool by finding the operations sequence to create the various features and geometries in a design. See-Toh et al. (1995) applied features extraction, where for bending features the system debriefed the unfolding angle from the 3-D part and the bending allowance was calculated based on suggested tooling available, then the approach performed simple rotation and transformation of faces to compose the final 2-D print.

Another approach based on feature extraction was followed by Wang et al. (1996), where the work developed a concurrent design system that functioned with features and by controlling the various relationships between the different representations of sheet metal parts, hence the system used multiple representation schemes of the sheet metal part to follow the part's changes through each manufacturing step. The key was to relate the topology of the part during the different stages of manufacturing where the representation can be transformed from one type to another or from one dimension to two

dimensions, and so on. The aim was to provide concurrent design for process and product design phases and remove any vagueness for product representation, and to modify the design of a sheet metal part by closely relating it to a process model. The designer was capable of adding, subtracting, or modifying a feature by recalling a process model with specific parameters rather than changing the drawing and design of feature.

Wang et al. (1997a) discussed the design and production planning for sheet metal bending process based on categorizing features in combination with precedence rules that were generated at the design process, the research used features to propose precedence rules, select tool, and determines the grasp and motion approaches. Subsequently, the selected features were used to aid the process planning phase, since the features provide valuable encoding of known information. The system also included feedback for special features in bending that can cause manufacturing problems.

Other strategies considered different inputs for the design of the sheet metal part other than the 3-D model, Shunmugam et al. (2002) discussed the formation of 2-D foot print for metallic sheet products from orthogonal projection without the need for the complete 3-D design by extracting the features illustrated in the orthographic projections then produced the 3-D wireframe, the approach used attributes to extract the characteristics of each bending operation and then counted in for the bending allowance. However, ambiguity in projected views limited its scope and the approach was not suitable for a general class of complex sheet metal products. The basics of the system depended on curved faces transformation and rotation while accounting for the bending allowance based on the traditional tooling used.

In spite of the effectiveness of feature extraction method to transform the sheet metal deign from one representation to another, it is not sufficient to consider Origami-based sheet metal products due to the successive bends in such products and the lack of traditional tooling requirements that essentially identify the nature of features to be extracted. In addition, the approach is not capable of identifying the various flat patterns that can be folded to generate the same 3-D part or to enumerate them, rather the feature extraction approach utilized recognizable features to track back how the 2-D footprint should be cut out of strip based on unrolling few bends, then the output can be utilized to generate a bending sequence plan.

The second approach for the design of sheet metal parts that includes considerations for bending operations is based on expert systems, where design guidelines and rules are stored in a system after being extracted from the experience that designers develop through their design activities.

Soman et al. (2003) developed an expert system with 17 grammar rules for manufacturing operations for sheet metal products to handle the complexity of sheet metal product design, the grammar rules handled simple operations performed on sheet metal parts as bending, notching and slitting. The system aimed at checking manufacturing constraints and avoiding considering infeasible design choices. However, the considered operations within the 17 grammar rules were not enough to cover all operations and geometries types to fabricate a sheet metal product. Another practice was to build a cases database for feasible designs and building a knowledge-based engineering system as the one Sandberg et al. (2006) developed for sheet metal products.

However, this approach was limited by the cases types represented in the databases to match new designs and operations, in addition to the extensive efforts required to build and modify the cases database.

On the other hand, Patel (2008) presented grammar based system with graph representation for sheet metal parts, The objective of Patel's dissertation is to create a tool for design automation that replaced designer's creativity for sheet metal products that are manufactured by the traditional manufacturing processes by building an expert system of 108 design grammar rules, his dissertation utilized a software named Graphsynth developed by Campbell (Campbell and Rai 2003 , Campbell 2006) to define graph grammars or rules. The research did not propose a new methodology for the design automation; rather the design automation was applied to generate sheet metal parts designs. While my dissertation aimed at establishing a design procedure for the folded sheet metal parts by extending paper-based folding technique, i.e. Origami principles that are a new trend in forming sheet metal products by a set of sequenced folds that can be performed without the need for hard tooling such as the set of dies.

In terms of input to the system, Patel's tool initiated the analysis with identifying the spatial constraints for the part that represented the functionality of the part, where no design embodiment exit, actually the tool objective was to generate a suggested design for the final 3-D part, hence no topological or geometrical information were fed to the system. , rather his tool intended to substitute the designer by iterative exploration of available search space. For my dissertation, a detailed design embodiment was required to initiate the analysis since the design procedure handled the possible designs to

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transform a 3-D part into 2-D and vice versa, while Patel's work considered the design of 3-D part without any concerns to its 2-D layout.

Both dissertations used graph models, however they were different in the objective and the tasks a graph performed, in addition to the differences in representation scheme that each approach modeled. Patel's dissertation used the graph model to check design grammar rules and govern their actuating sequence, besides all the mathematical information stored in the graph were referring to the variables associated with the grammar rules that were denoting each manufacturing operation, such as the length of a slit or the location of a notch. Hence the graph representation could not be manipulated or extracted to conduct further analysis outside the environment of GraphSynth, which meant that the representation was not generic and it was dedicated to serve the grammar rules only. The graph in his work represented a hatched area of the suggested design by a node, where each linking edge in the graph represented a localized line separating two hatched areas, which did not necessarily represent a manufactured feature or a bending line, rather the edge in the graph model assisted in determining the limits to the variables associated with each operation of the five. In my work, the graph modeling was used to extract the topological information of the predefined 3-D part design and converted it into mathematical form that can be manipulated easily by any programming environment, where the graph referring to a 3-D part topology was named Face Adjacency Graph (FAG) , in which each nodes represented a face of the part and each link was an actual bending or welding edge in the part, hence FAG had a physical meaning for each link that represented a manufactured feature, in addition the mathematical information

extracted from the FAG was explicit and denoted the actual topology of the 3-D part regardless the programming tool used.

The author developed a knowledge base of 108 design rules that were extracted and stored from the sheet metal design science; the rules governed the manufactured features in each suggested solution by defining the values for each variable associated with each operation. For example, if the system selected a slit to be manufactured, then the rules defined its length relative to other features. However, the developed guidelines or grammars that were related to bending operation defined the angles and location of bends based on the traditional manufacturing process for bending the metallic sheet with a set of dies, therefore the iterative search for design solutions excluded any bending operation with sharp angles and sequential or multiple bending steps due to tool accessibility, hence it cannot be used to design sheet metal products by fold forming with material discontinuities along the bend line as in the main focus of my dissertation, which dealt with the design of folded sheet metal products based on its transformation from 2-D to 3-D and vice versa, where Patel's design automation tools did not investigate such transformation or discussed the various 2-D design that all can be folded to the final 3-D design.

On the contrary to my work, the graph representation used by Patel was not sufficient to investigate the various possibilities to fold a sheet metal product out of 2-D flat pattern or to distinguish between a weld line and a bend line of the product. His work rather used the graph representation to determine the variables limits for each operation, and the topology phase altered one or more of the variables to generate a new solution

and then checked the validity of it based on the grammar rules. Moreover, the graph representation was used solely to govern the activation of design rules and explore the search space.

Patel's exploration of the possible designs for the same part was limited by the 108 design grammar rules that were fed into the system, this bounded the scope of the possible candidates and it could not guarantee the optimality of the generated designs in terms of topology or geometry. In my dissertation the design procedure scan's all possible options for 2-D flat pattern design since the developed graph traversal algorithm explores all the possible combination of bending arrangements by traversing all possible tracks on graph based on permutations, hence an investigation of the topological and geometrical optimality can be conducted.

In addition, in Patel's dissertation the designs of the possible candidates were not necessarily similar with respect to geometry or topology, which cannot serve the fold forming process since the user was not allowed to define any operation within the phases of the technique, thus the final output did not necessarily have a bending operation to be performed. Moreover, the produced solutions to the design problem were not rated or judged regarding any metric or index in order to evaluate or rate the designs based on parameters that reflect easier handling or manufacturing cost associated with design compactness , nesting efficiency, and welding cost. Rather the system generated some possible designs and left the evaluation to the user. On the other hand, in my dissertation the design approach was developed to consider sheet metal products with folding operation and to investigate all the possible designs in terms of the same topological and

geometrical aspects, then rate the possible designs based on optimization metrics reflecting the cost and manufacturability differences among the flat pattern candidates.

Patel's work served as an expert system for the design of sheet metal from scratch in terms of the five operations listed previously by investigating the search space in a process defined as tuning and pruning, where a random design was suggested by the system as a seed to the search, then the searching tree for each iteration either eliminated or added a new variable, i.e. one dimensional characteristic for one operation of the five possible operations, after that the procedure investigated the possible candidates. However, the results varied in terms of geometry and shape since the user defined conditions are only based on spatial constraints. In addition, the search space was heavily dependent on the search tree generated, which made each proposed solution dependent on the set of rules applied to prune or tune it, therefore the searching direction was not expanding in all possible tracks. This approach can lead to good suggested solutions, however the output was not all of the possible combination of solutions. In contrary, in my dissertation the search investigated the number and location of both seam lines and bend lines, besides the number and combination of all possible flat pattern for the same geometrical and topological constraints before proceeding to a completely new design of the 3-D folded sheet metal component with material discontinuities along the bend line. Hence, the search space is covered and all feasible designs were investigated.

In conclusion, Patel's presented an expert system able to automatically produce a design embodiment for the functional requirements of a sheet metal product in the scope of five main manufacturing operations, i.e. slitting, notching, bending, shearing, and

punching. In spite of the fact that he included bending operation, the output does not necessarily have a bending operation to be performed and the design was excluded if sharp angles and multiple bends are suggested, hence it could not handle the type of sheet metal products my dissertation tackled, moreover no concerns were given by Patel's to the 2-D footprint of a final suggested design, hence the output design is not guaranteed to be manufactured out of a sheet metal strip by bending only, rather my dissertation tackled a different type of a problem, that is the design of folded sheet metal products from 2-D aspect to the 3-D and vice versa while initiating the analysis with a full detailed embodiment of the 3-D design. In addition, the two approaches handled different manufacturing techniques, Patel's tool investigated the traditional manufacturing operations conducted for sheet metal products, however my dissertation focused on a new technology to fabricate sheet metal products by folding only while having material discontinuities along the bend line that enables the creation of sharp angles and a sequenced sets of folding operations to be performed. In spite of the fact that both dissertations used graph models, the representation essence, the purpose, and the task each graph model served were completely different. In addition, the search space that Patel's work scanned was limited to the design rules stored in his system, while in my work the search space was constructed based on traversing algorithm that accounts for each possible permutation , hence it covers all possible design combination.

Other published work devoted for applying expert system for the design of sheet metal product can be found in Dastidar et al. (1991), Poli et al. (1993), Mantripragada et

al. (1996), Tang et al. (2001), Tu et al. (2001), Tang et al. (2003), Liu et al. (2004), Tang et al. (2004), Chen et al. (2005), Ramana et al. (2005), and Kumar et al. (2006).

The utilization of expert systems to design and generate flat patterns is promising; however it demands a ready and established design guidelines and expertise to explore all possible flat patterns designs in case of bending Origami-based metallic sheets, which in current state-of-art is not present. Moreover, the complexity of bending metallic products with sets of successive folding operations requires more investigation before being programmed into expert systems in terms of minimum number of bending lines requires and the different orientations of bend and weld lines. Furthermore, the effectiveness of an expert system is heavily dependent on the type of knowledge and experience stored in it during the programming phase, hence it captures the experience built over years for sheet metal products within a facility but it is not explicitly capable of dealing with new forming technologies for sheet metal products as in the case of fold forming for Origami-based sheet metal products.

The Flat Pattern Analysis (FPA) of sheet metal products includes the enumeration of all possible 2-D patterns that can be feasibly folded to generate the part. Also FPA should include a set of selection criteria to choose the most optimized design; the following chapter discusses a set of optimization metrics developed in this work. Studies that investigated the flat pattern generation in non-traditional manufacturing conditions, i.e. zero-thickness and zero- bending radii, have been presented in literature, Shpitalni (1993) developed a systematic approach to design and manufacture sheet metals through bending flat 2-D strips. The products are first defined based on the principles of zero-

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thickness sheets and zero-bend radii, in addition to a set of manufacturing constraints that transform the 2-D layout into a 3-D part. Conversely, the formation of flat layouts is determined through connecting the nominal facets found in the part 2-D drawing i.e. the part's different projections or views. This approach cannot explore all possible layouts, particularly when many faces exist. Hence there is no guarantee that an optimized flat pattern design is selected.

In a following publication, Shpitalni et al. (2000) defined a technique for the conceptual design of sheet metals through sketching. This approach included a step to determine the 2-D layout patterns based on the A* search algorithm that uses an optimal heuristic search for a graph. This approach is found to yield good solutions. However, the search code is inefficient because it can consider the same flat pattern multiple times when generating an output. To solve this, arbitrary indices can be assigned for the links while connecting them in monotonous order only.

Automating the FPA was also discussed by Lin et al. (1998). They developed a set of mathematical models to relate the topological properties of a 3-D thin-walled object to the 2-D layouts. The work focuses on generating a number of seam lines that are necessary to split the 3-D part into a 2-D layout using a formula based on mechanism theory. The use of such theory is based on an observation that developing a thin-walled object is comparable to unfolding an open-chain spatial mechanism. Subsequent steps included the identification of the feasible seam arrangements, the generation of flat patches that correspond to the faces by applying a simple closed-path theorem. Finally, the code generated all the reasonable flat patterns. The proposed technique can also

reduce the computational effort in the unfolding process. However, the main equation used to produce the number of seam lines is not valid for structures with hyper-common edges (edges that connect more than two faces).

Lipson et al. (1998) handled the topological properties of sheet metal parts through a schematic representation while assuming it to have zero-thickness and zero bend radii; the work established a general topological invariant that relates the number of faces, components, bends, free edges, welds, vertices holes and volumes. This invariant established an important condition for the validity of a sheet metal product schematic representation from a topological point of view. Moreover, the study can determine the number of bend lines for the flat pattern in order to keep the component faces joined, which can be useful in a comparison based on the required bending steps among the various flat pattern designs. On the other hand, Liu and Tai (2002) focused on a computer representation for the connectivity of the 3-D folded structure faces using a graph-theoretic model. Then, an overlapping detection algorithm is applied to each unfolded flat layouts to check for any overlapping faces. The field of application of this development is focused on folded paperboards that are manufactured in forms of sheets to serve as packaging cushions. This model can also be applied to folded metal sheets because the structure is similar in terms of the geometrical and the topological aspects. Nevertheless, the method does not consider how the folded structure can be held standing in place after folding. Also this approach is not accurate when an edge in a part connects more than two faces (hyper-common edge). This shortcoming was handled in a following work by Tai et al. (2004), where he developed an algorithm to detect topologically invalid spanning

trees in the unfolding subroutine; hence invalid cases due to hyper-common edge complications can be eliminated.

Optimality measures were also discussed by Liu et al. (2007) to help develop selection criteria for the generated flat patterns. The study extracted the flat patterns based on the number of spanning trees, and the compact output technique developed by Shioura et al. (1997) to enumerate all the spanning trees of a graph. Moreover, an algorithm is applied to ensure the geometrical validity of the generated flat layouts by detecting the case when faces are overlapping. The optimality was based on the generated flat patterns compactness index. The derivation of this approach focused on the packaging requirements for folded paperboards; yet, when extending it to sheet metal parts, new issues should be considered. Such issues include the manufacturability and material utilization, which can be evaluated through quantifying nesting efficiency.

2.3 Representation Principles and Constraints

2.3.1 Representation of 3-D Structure

In order to conduct the FPA, a decision needs to be made on the representation model for the 3-D geometry. There are two main geometric modeling representations that can be used, being; boundary representation (B-rep) and solid representation; where in a B-rep a structure is modeled as a set of surfaces that encounters the structure material, for example a cube is set of squared surfaces, while the solid representation expresses the set of all points that are encountered in the cube (LaValle 2006). In folded sheet metal application, boundary representation is sufficient to translate all needed geometric and

topological information, where geometric data communicates the shape of structure, while topological data describes the connectivity between surfaces (Liu and Tai 2002). Figure 2.2 illustrates the B-rep elements and the relation between them identified by (Stroud 2006).
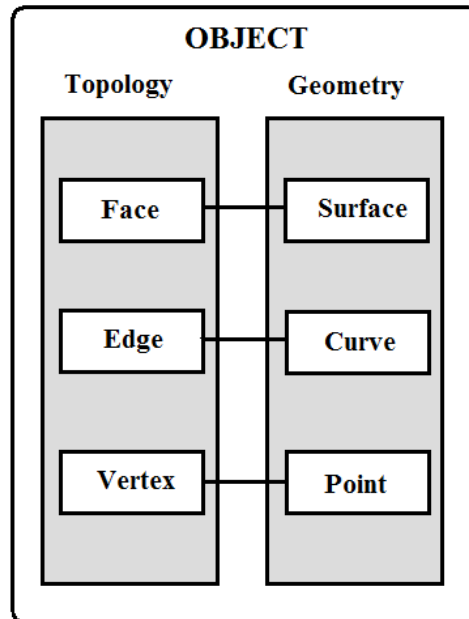
Figure 2.2 Elements of B-rep.

2.3.2   Representation of 2-D Layout

In order to apply the FPA for sheet metal parts with a defined thickness, some assumptions need to be made to simplify the investigation. This work adopts the construction principles and the manufacturing constraints proposed by (Shpitalni 1993). The construction principles determine the nominal layout by assuming that the flat pattern layouts are a group of facets connected to each other along the bend lines. A facet is the major entity in the analysis and it is a planner entity bounded by bending lines with at least one of them being straight. These facets are paper-thin walls while their bending

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is performed with a sharp or zero bending radius tools. Hence, sheet metal parts are represented schematically without bending allowances. This principle is valid for bending metal sheets along a bend line with discontinuities because no bending punches are required nor assumed. Moreover, these construction principles assume that the sheets are manufactured by folding operations only.

In terms of the manufacturing constraints, these are the set of rules that describe the transformation of the proposed layouts into the real 3-D part. A manufacturing constraint sets the dimensions of the nominal layout as either inner or outer dimensions. This assigned attribute for the layout can be useful once the final geometry will be considered and the material thickness will be added. Figure 2.3 illustrates the variation in the generated 3-D geometry, when the layout is set as inner or outer dimensions.
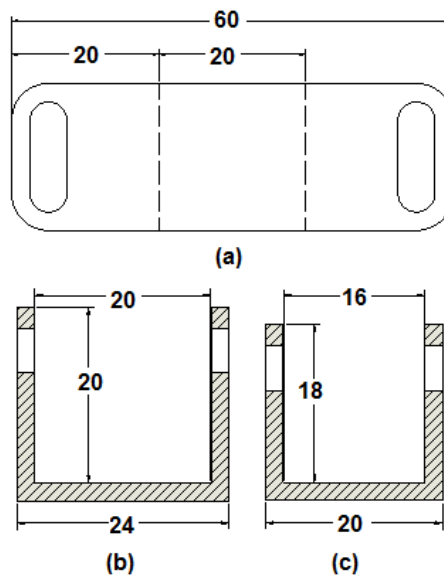
Figure 2.3 Variation in resulted geometry foe inner and outer dimensions assumptions.

(a) 2-D layout, dimensions in cm. (b) Final folded geometry for inner dimension assumption. (c) Final folded geometry for outer dimension assumption.

2.3.3 Anatomy of Sheet Metal Parts

The selected parameters and terms referring to sheet metal parts and components can be shown in Figure 2.4, the sheet metal part is a collection of surfaces in different planes named faces connected to each other by common edges and surrounded by free edges and common edges. The point where any two edges meet is a vertex. In order to unfold or unroll all the surfaces of the part and place them on one plane without being stretched or distorted a 2-D pattern is generated. However this unfolding procedure requires some common edges to be broken, these broken ties of faces connections referred to as seam or weld lines. The free edge refers to any edges that cannot be a bend or a seam lines. The different combinations of seam lines produce multiple flat layouts that all can correspond to the 3-D structure. Two types of opening internal features can be seen in sheet metal parts those are rings and holes, where a ring is an edge loop interior on a face and it is disconnected from the face boundaries, A ring can be neglected since it is a local feature and independent from the part's topology, while a hole is an opening that intersects with one bend line or more (Lipson et al. 1998). The number of holes in a part is the genus of the flat pattern and is denoted by g in Euler-Poincaré's formula for manifold objects (Mantyla 1988) and g_{nm} for non-manifold objects by (Lipson et al. 1998). A manifold geometry is the structure that satisfies certain topological conditions; where (i) all edges separate exactly two faces, and (ii) All vertices are surrounded by a single loop of faces. The non-manifold shape is the geometry that violates some of the topological conditions.
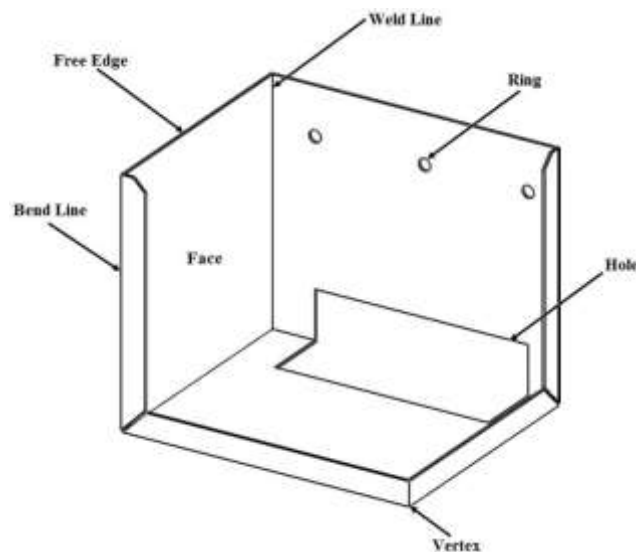
Figure 2.4 Components of sheet metal structure

2.4   Determining Flat Patterns by Unfolding

2.4.1   Representation of Topological Information

The unfolding process of a 3-D structure can produce many potential 2-D layouts that can be successfully folded to the desired shape. To generate these possible 2-D designs the topological data of a 3-D structure will be extracted and will be represented using a graph model, where each face of a 3-D part is symbolized as a node while each edge connecting two faces is denoted as a link as shown in Figure 2.5. In graph theory, the graph G (V, E) is defined as a mathematical structure with two finite sets of vertices (V) and edges (E). The elements in V can be interpreted as nodes and each E has a set of one or two vertices associated to it (Gross et al. 2006). The type of the graph associated

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with unfolding applications is undirected graph since there is no difference between

linking face 1 to face 2 or vice versa.
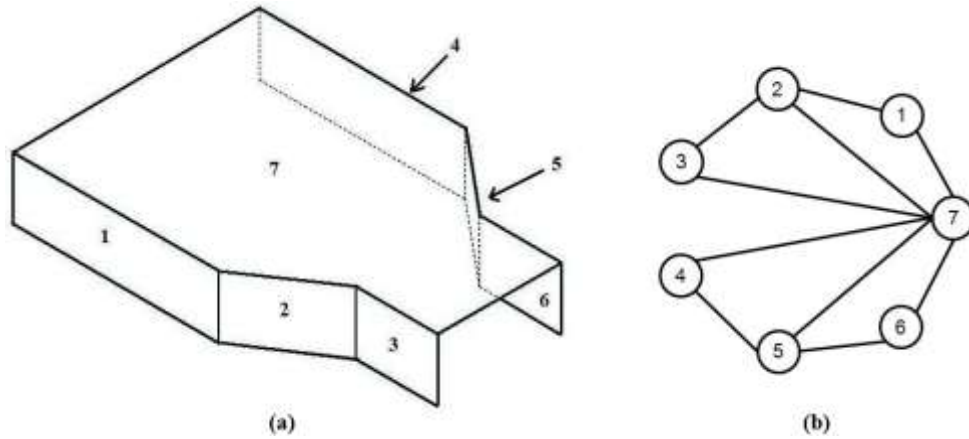
Figure 2.5 Representation of structure topology. (a) Faces of 3-D geometry. (b) FAG for

3-D structure.

The conceptual interpretation of the set of connected nodes that refers to a 3-D

structure results, is known with the term Face Adjacency Graph (FAG), this can be

numerically represented by adjacency, incidence, and degree matrices. Matrices are

forms to translate the topology information of the geometry into an input that is used in

further calculations. The adjacency matrix of a FAG, referred to as matrix *A,* which is a

square symmetrical matrix and the rows and columns represent the faces of geometry or

nodes in a FAG, the entries of such matrix can be either 0 or 1 such that:

$$A_{(a,b)} = \begin{cases} 1, & \textit{if face a \& b are connected} \\ 0, & \textit{otherwise} \end{cases} \tag{2.1}$$

Where $A_{(a,b)}$ is the entry of the adjacency matrix for the row of face *a* and the column of face *b*. For example, the adjacency matrix for FAG shown in Figure 2.5 can be as follows:

$$A = \begin{bmatrix} 1 & 1 & 0 & 0 & 0 & 0 & 1 \\ 1 & 1 & 1 & 0 & 0 & 0 & 1 \\ 0 & 1 & 1 & 0 & 0 & 0 & 1 \\ 0 & 0 & 0 & 1 & 1 & 0 & 1 \\ 0 & 0 & 0 & 1 & 1 & 1 & 1 \\ 0 & 0 & 0 & 0 & 1 & 1 & 1 \\ 1 & 1 & 1 & 1 & 1 & 1 & 1 \end{bmatrix}$$

On the other hand, the incidence matrix, denoted by *I*, describes the relation between the nodes and links of a FAG, the rows refer to the nodes while the columns refer to the links, such that:

$$I_{(n,L)} = \begin{cases} 0, & \text{if no link} \\ 1, & \text{if link between } n \text{ \& } L \\ 2, & \text{self-loops} \end{cases} \qquad (2.2)$$

In the unfolding application, no practical meaning exist for self-loops where the two endpoints of a link are at the same node. One attribute of incidence matrix is that the summation of each column equals to 2.

Another representation form is the Laplacian matrix, *L*, also called Kirchhoff matrix. It describes the number of connections between nodes x and y, and occurrence of connections at one node, such that

$$L = \begin{cases} d(i), i = j \\ -k, i \neq j \end{cases} \qquad (2.3)$$

The $d(i)$ is the degree of the ith node and it stands for how many connections or links occur on that nodes, k denotes the number of connections between node i and j. For purposes of this research the connectivity is represented by face adjacency matrix.

2.4.2   Possible Number of Seam/Weld Lines

The number of possible layout arrangements can be determined by extracting all spanning trees of the FAG associated with the 3-D structure, a tree in a graph world is defined as a connected graph with no cycles, while a spanning tree of a FAG in an unfolding application is a tree that contains all nodes and some of the connections or edges in the FAG. The decision of which edge exists in the spanning tree determines which two faces of a folded sheet metal will be connected by a folding line, while the edges that do not exist indicate welded or joined edges. Equation (2.4) represents a formula that is developed based on spatial mechanisms to calculate how many edges in a 3-D geometry will be broken to flatten a thin-walled structure (Lin et al. 1998); these edges are referred to as seam lines. Hence, the equation predicts how many welded or joined edges will be in a sheet metal part formed by folding. The use of such theory is based on an observation that developing a thin-walled object is comparable to unfolding an open-chain spatial mechanism.

$$N_s = N_e - N_f + 1 \hspace{2cm} (2.4)$$

Where, N_s is the number of seam lines. N_e is the total number of common edges. N_f is the number of faces. Figure 2.6 shows a tunnel shaped part with four faces and four common edges. According to Equation (2.4), a total of one seam line is needed to unfold the part.

Equation (2.4) indicates that the number of edges that will be subjected to folding, denoted by N_{fold} , equals the number of seam lines subtracted from total number of common edges (Liu and Tai 2002), such that :

$$N_{folds} = N_e - N_s = N_f - 1 \qquad (2.5)$$
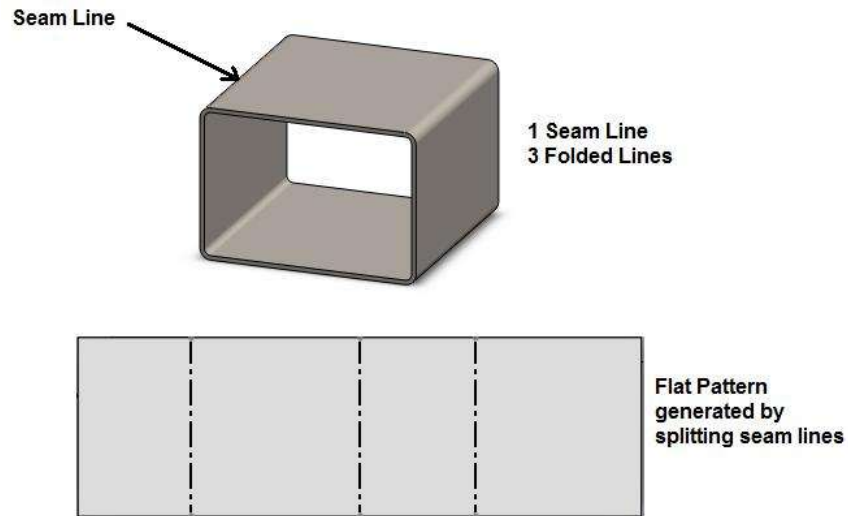
Figure 2.6 Application of seam line to unfold a structure.

This result is consistent with the fact that for each tree of an undirected graph with *n* vertices the number of edges will equal *n-1*. Yet equation (2.5) is not applicable to non-manifold objects with common edges linking more than two faces. The weld lines are considered necessary to hold the part together and the minimum number of weld lines can be calculated using a general topological invariant, *F*, which is based on Euler-Poincaré's formula, such that :

$$F = s + L + E + w - V - g_{nm} + k \qquad (2.6)$$

$$D = V - E + g_{nm} - k \qquad (2.7)$$

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Where, F is the number of faces. V is the number of vertices. E is the number of all edges. s is the number of disconnected flat patterns. L is number of bend lines. g_{nm} is the genus of flat pattern. w is the number of weld lines. k is the number of volumes corresponds to a closed surface. D is the difference between actual number of bends or weld lines and the required number required to hold the geometry together.

2.4.3 Counting Number of Flat layouts

As previously discussed, the number of flat layouts that exists for a specific 3-D structure depends on how many spanning trees can be extracted from the FAG. This can be calculated by applying matrix-tree theorem that involves generating a reduced matrix of the Laplacian matrix through deleting one row and its corresponding column. The determinant of reduced matrix is the number of possible spanning trees, which alternatively means the number of possible flat layouts. Alternative ways can employ incidence matrix I, where the number of spanning trees equals the determinant of $\tilde{I}.\tilde{I}^T$. Where $\tilde{I}$ is a reduced matrix of I produced by deleting the last row of I, and $\tilde{I}^T$ is the transpose of the reduced matrix.

Furthermore, the number of seam lines, N_s, and number of common edges, N_e, shown in equation (2.4) can be used along with a new variable N_n , which indicates the number of non-straight common edges, and can be used to calculate the number of the different possible patterns (Lin et al. 1998), such that:

$$P = B(N_e - N_n, N_s - N_n)$$ (2.8)

Where $B(i,j)$ is the binomial coefficient.

2.4.4 Application of Graph Traversal

After extracting the topological characteristics of a 3-D structure into a FAG, the next step in FPA is to determine the topological characteristics of the flat pattern by processing the FAG. The processing aims at determining all spanning trees that exist in the FAG, each spanning tree can potentially represent a flat pattern design. Analyzing FAG to extract spanning trees is known as graph traversing process, where the procedure travels from one node to another by visiting all nodes, while no edge in the graph is visited twice in the case of sheet metal folding application. Many graph traversal algorithms are developed in the literature to be mainly applied for networking and graph analysis. However, the feasibility of such algorithms is not investigated in literature for FAG that refers to folded sheet metal components. The rest of this section studies major graph traversal algorithms along with their possible applicability to folded sheet metal analysis.

Breadth First Search

Breadth First Search (BFS) is a major search technique considered as the basic block for many graph traversal algorithms. Using BFS to traverse the FAG of a folded sheet metal part generates one tree that refers to a single flat pattern, named Breadth First Tree (BFT), which is the shortest path for un-weighted graph. However, investigating the physical meaning of the BFT in folded sheet metal applications can result in different sets of bending arrangement that are characterized based on the definition of a base face, since the BFS starts traversing from a selected node referred to as root node, which represents a base face in the FAG. Applying the BFS for folded sheet metal produces a

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flat pattern with most of the bending edges is concentrated on the bases face. Consequently, the base face owns the highest number of bending edges. Figure 2.7(c) and (f) show the BFT and its corresponding flat pattern for a tetrahedron made of sheet metal. Therefore, the BFT requires less adjusting and orientation operations during folding process, and selecting the base face based on manufacturing complexity induces a base face that is the largest in area, to help minimize the length of the cut material and welded or joined edges. The other selection aspect is based on the face with largest number of bending edges to minimize the sequential orienting operations upon folding.
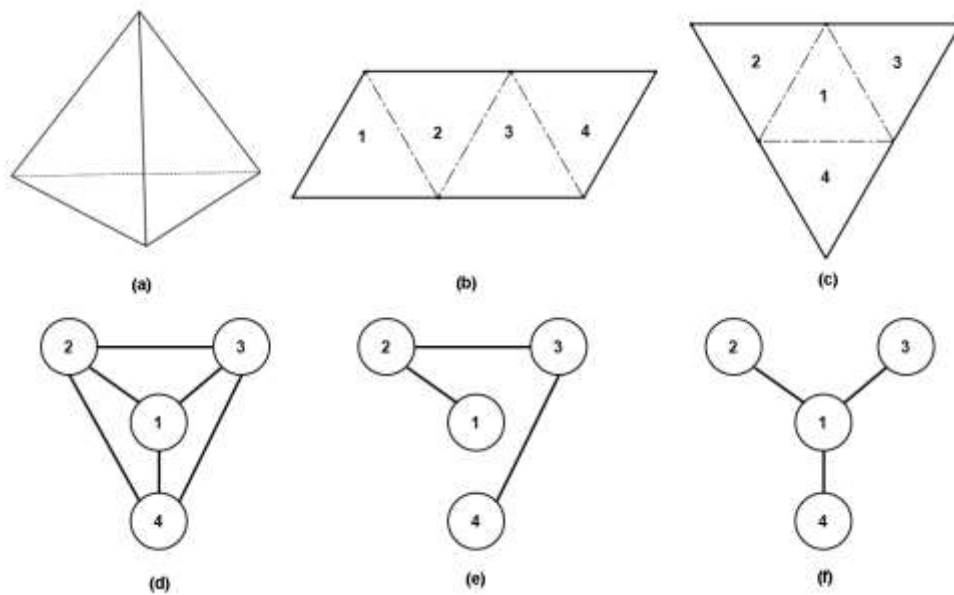
Figure 2.7 (a) 3-D geometry of tetrahedron made of sheet metal. (b) DFS flat pattern. (c) BFS flat pattern. (d) FAG of folded tetrahedron. (e) DFT. (f) BFT.

Depth First Search

The second discussed traversal algorithm in this work for folded sheet metal parts is the Depth First Search (DFS). In contrast to BFS, the visiting systematic order selects

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the child nodes in FAG before the siblings. DFS produces a single tree for each FAG, named Depth First Tree (DFT). Traversing a FAG for folded sheet metal part using DFS generated a spanning tree with bending edges distributed among all faces .Figure 2.7(e) shows the DFT for tetrahedron made of sheet metal, it gives the combination of bend lines for each face as follows ; faces{1,2,3,4} number of bending edges connected to faces are{1,2,2,1}, respectively. However for the other flat pattern shown in Figure 2.7(f), the bending edges are {3,1,1,1}. It can be concluded that in DFT no single face owns most of the bending lines.

The practical implementation of BFS and DFS differ in terms of computational time required to generate a spanning tree as well, since the speed to reach a certain face is not similar. However this is not a main difference in folded sheet metal application, since the FAGs do not have large number of nodes i.e. sheet metal parts have relatively small number of faces compared to other applications.

On the contrary, BFS and DFS differ in terms of the FPA computation time during the final step; that is the generation of the 2-D CAD model of the flat pattern. Since this step involves the rotation of faces geometry around the base face plane. Hence, the number of nodes between one node and the root node, denoted by k, represents the number of rotating stages required to settle this face on the same plane of a base face, such that each face experiences k+1 rotations. BFT consumes less time to pass through this step, as it is the shortest un-weighted path tree from root node to each other node.

Prim's Algorithm

The examined algorithm for folded sheet metal parts up to now dealt with un-weighted undirected graphs. Un-weighted edges of a graph imply that there are no preferable criteria set in selection of bend lines represented in a tree. Instead the selection of a base face controls the bend lines arrangement due to the predefined traversal method. However, it is necessary to consider a cost function or a penalty scheme to evaluate the designs in terms of its manufacturing cost. The welding cost metric is the main value that differentiates the various flat patterns, which all are equal in total faces area and minimum number of bend lines. Hence, the different bending arrangements are not the same in terms of welding requirements. If the long edges in a flat pattern are all produced by folding, then the cost to weld such a structure will be the minimum.

In order to locate the flat pattern with the minimum welding cost, all the combinations of folding lines will be investigated; consequently all valid spanning trees are searched based on the set of links connecting nodes. This problem is solved in this work using the Minimum Spanning Tree (MST) generation by employing Prim's algorithm, which finds a tree for the weighted undirected graph i.e. Weighted Face Adjacency Graph (WFAG). Therefore, the traversed tree connects all vertices and has the least summation of links' weights among all other valid spanning trees. The assigned weight for each link is a numerical value symbolizes preference for each link to be in the traversed tree. For the folded sheet metal application the weight is indicating the cost for welding edges, which can be directly related to the edge's length. Since the optimization

criterion is minimization, the lesser the weight assigned to an edge, the higher its welding cost is. Thusly, the weight point-out favorability when assigning an edge for welding; otherwise, if the designer indicates the weights by explicitly expressing a welding cost, then the best flat pattern will be corresponding to the maximum spanning tree, which excludes all edges with least cost from the flat pattern.

The weights are assigned using edge-weight matrix that is $(L, 3)$ in size, where L is the total number of edges in WFAG. For each two connected nodes N_i and N_j the third column specifies the cost to select that edge denoted by W_{ij} such that:

$$\text{Edge-Weight Matrix} = \begin{bmatrix} N1 & N2 & W12 \\ N1 & N3 & W13 \\ . & . & . \\ . & . & . \\ Ni & Nj & Wij \end{bmatrix} \quad (2.9)$$

For structure shown in Figure 2.7 (a), the edge-weight matrix can be set as the following matrix, while the WFAG for that structure is shown in Figure 2.8 (a).

$$\text{Edge-Weight Matrix} = \begin{bmatrix} 1 & 2 & 3 \\ 1 & 4 & 3 \\ 1 & 5 & 3 \\ 2 & 3 & 3 \\ 2 & 5 & 1 \\ 3 & 4 & 3 \\ 3 & 5 & 3 \\ 4 & 5 & 1 \end{bmatrix}$$

Solving the WFAG shown in Figure 2.8(a) for the MST using Prim's algorithm produces a tree with total weight of 8, shown in Figure 2.8 (b).
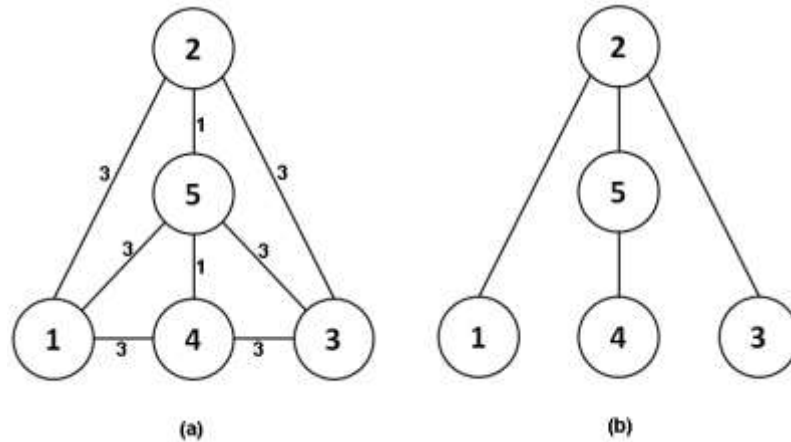
Figure 2.8 (a) WFAG for open box structure. (b) resulted MST for open box structure.

A* Search

Another possible scheme for folded sheet metal parts that can incorporates welding cost into the traversing algorithm is the A* search. It is mainly employed for path finding between two known locations; an initial location or node and final destination. The selection of such path is based on the minimum cost allocated to the travelled links or edges. The application of that approach to unfold a 3-D geometry is possible; however the approximation between finding a spanning tree that represents a flat pattern and traversing a graph to find optimal path needs extra constraints. Therefore, A* search is required to travers the WFAG from an initial selected node to a goal node while visiting all nodes i.e. forming a spanning forest, whereas there is no edge visited more than once in addition to achieving the minimum total cost tree.

The WFAG is traversed from one node to other based on a pre-identified instruction or rules; as the A* search heuristics applies best-first search. The assigned instruction for folded sheet metal is the state of cost for each face as selected in the final

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spanning tree; this can be classified into two terms. The first is the cost of the edge i.e. welding cost; while the second is the cost estimated to reach the endpoint face from the current state .The second term of cost can be interpreted for folded sheet metal applications in terms of total number of bending edges in a flat pattern. Since the seam lines equation predicts how many edges will be broken or split to unfold a 3-D structure, then the cost to reach the final face can be indicated by how many links left available to be classified as bends once one edge is travelled. Hence, if a WFAG has f number of faces, and the search traversed L links in one partial state, then cost to reach the final state will be given by Equation (2.10)

$$(f - 1) - \text{L} \qquad (2.10)$$

Where $f\text{-}1$ is the minimum number of bend lines for a resulted flat pattern that discussed previously.

The resulted flat pattern by conducting A* search is found to be the same one for MST, since both aim at discovering the minimum total cost of welding edges. However, A* search is less efficient in terms of application; since more constraints are needed to make it applicable. Furthermore, it can consider the same flat pattern several times for search by triggering the same links but in different orders. An additional step is required to solve this issue to uniquely identify the links and the visiting order (Shpitalni et al. 2000).

Enumerating All MSTs

The previously applied MST calculates the flat pattern with minimum welding cost. However, if there are two edges in a 3-D geometry that are identical in terms of

cost, then there might be more than one MST that are identical in terms of total cost as well. It can be seen in Figure 2.8(b) that exchanging the links connecting faces 1-2 with link 1-4 will generate a spanning tree with the same total weight of MST, in fact since 6 edges out of 8 have equal integer weights there will be multiple MSTs with the same total weight, which implies that several flat patterns will have the same welding cost. Nevertheless, their bending arrangement is dissimilar. This fact imposes permutations of one MST by exchanging one selected edge with its identical one cost-wise.

To solve this issue and investigate the different manufacturing characteristics of generated flat patterns, an algorithm for listing all the MSTs developed by (Yamada et al. 2010) is utilized. After a MST is found using Prim's algorithm, the enumeration for all MSTs routine is activated to search for other possible flat patterns with minimum welding cost. The investigation of dissimilarity within flat patterns with the same welding cost in terms of manufacturability showed no fixed trends in manufacturing characteristics, such that the designer cannot predict the best MST for best bending orientation or welding tools accessibility.

Alternatively, generating all MSTs restraints the selection to a smaller set for an optimized flat pattern in terms of welding cost only, afterwards the geometrical aspects can be utilized to favorably rate the flat patterns in terms of manufacturability.

Enumerating Algorithms

The need to produce an optimal design of sheet metal parts cannot always be uniquely considered within the traversing algorithm; the manufacturing aspect requires the flat patterns with the least consumed material of the sheet metal stock, while handling

and storage of flat patterns impose certain limitations on the acceptable length or width of a flat pattern. These needs cannot be explicitly translated into the applied graph traversal algorithm, since all inputs and outputs of this phase are topological information, whereas manufacturing and logistics needs are concerned with the geometrical aspects. Due to these reasons, enumerating all possible spanning trees of a graph is necessary for the subsequent selection criteria. All potential flat patterns are produced and evaluated in terms of an optimization index that reflects the geometrical needs for a sheet metal part.

Two approaches are used for enumeration; backtracking algorithm and compact exchanging algorithm. The first yields the spanning trees by incrementally building spanning trees through adding an edge to the graph, the method abandons the partial candidate spanning tree once it determines that it is not a valid complete one, hence the algorithm "backtracks" until a complete spanning tree is found. The efficiency of a developed algorithm that utilized backtracking technique is $O(N+L+NS)$ for time complexity and $O(N+L)$ for space. Where, S is number of spanning trees, N is number of nodes, and L is number of links or edges (Gabow et al. 1978).

In contrast, the second yields the spanning trees by exchanging one edge by a current one. The algorithm begins enumerating from a root spanning tree for the FAG, which can be produced by DFS , then extracts the potential trees by replacing one edge with another till all spanning trees are created. This technique explores each tree exactly once and extracts one spanning tree from another; hence it is characterized as compact. The time and space complexity of such scheme can be given as $O(N+L+S)$ and $O(N+L)$, respectively (Shioura et al. 1997).

Both of the applied algorithms traverse the graph differently and they are dissimilar in terms of time complexity. Nevertheless, the outputs are the same for each folded sheet metal part and all possible flat patterns are explored by enumerating the spanning trees. The only variance for sheet metal application is the order with which the flat patterns are produced. Though, this does not affect the final selected flat pattern since the optimization measures are used in the subsequent phase of enumeration step, and the designer cannot predict what would be the best geometrically optimized flat pattern from a partial set of spanning trees that does not contain all potential ones. Hence, all options need to be generated then investigated.

Developed Enumerating Algorithm

An enumeration algorithm, named Flat Pattern Enumeration Algorithm (FPEA), is established in this dissertation and integrated within the FPA tool to list all possible spanning trees. The FPEA is based on investigating all the possible routes to cross through the FAG by permutations. The FPEA structure is illustrated in the pseudo code shown in Figure 2.9, where the input for the algorithm is the FAG of a 3-D structure with N number of nodes and L number of links. The algorithm lists the available links for each node and stores them in a set of links for each node, afterwards the algorithm establishes permutations of all possible combination of links among nodes and generates possible spanning trees, for the generated spanning trees some can represent sub-components of the graph G that is disconnected graph, hence the FPEA examines the spanning trees and eliminates the invalid ones.

```
Insert graph G (V, N)
Collect links for each node
Establish possible links by permutations of all possible sets of links in a spanning tree s
Collect all generated spanning trees in set S
For each composed set of links check
If  ∀s ∈ S , composes a connected graph
Then store it in enumerated spanning tree set
Otherwise, delete s
```

Figure 2.9 Pseudo code for developed enumeration algorithm FPEA

The adjacency matrix is used to mathematically represent the FAG, where each 1 entry in $A(i,j)$ cell means there is a fold line connecting face i and j, where $A(i,j)$ is equivalent to $A(j,i)$ since the FAG is an undirected graph, the permutation of the 1 entry along each column generates different spanning trees. Afterwards, a modified adjacency matrix, denoted by A_{mod}, is extracted from the adjacency matrix such that the first column is zeros except $A_{mod}(1,1)$ equals to 1, the diagonal entries are always 1, as well. If $A(i,j)=$ 0, then $A_{mod}(i,j)=0$. In addition, $A(i,j) + A(j,i) =1,$ since they are equivalent and one entry is enough to conduct the calculations. For example, Figure 2.8 shows an open sheet metal box with 5 assigned faces with numbers from 1 to 5 along with its FAG. The adjacency matrix A of such topology and the modified matrix A_{mod} are listed below;

$$A= \begin{bmatrix} 1 & 1 & 0 & 1 & 1 \\ 1 & 1 & 1 & 0 & 1 \\ 0 & 1 & 1 & 1 & 1 \\ 1 & 0 & 1 & 1 & 1 \\ 1 & 1 & 1 & 1 & 1 \end{bmatrix} \qquad A_{mod} = \begin{bmatrix} 1 & 1 & 0 & 1 & 1 \\ 0 & 1 & 1 & 0 & 1 \\ 0 & 0 & 1 & 1 & 1 \\ 0 & 0 & 0 & 1 & 1 \\ 0 & 0 & 0 & 0 & 1 \end{bmatrix}$$
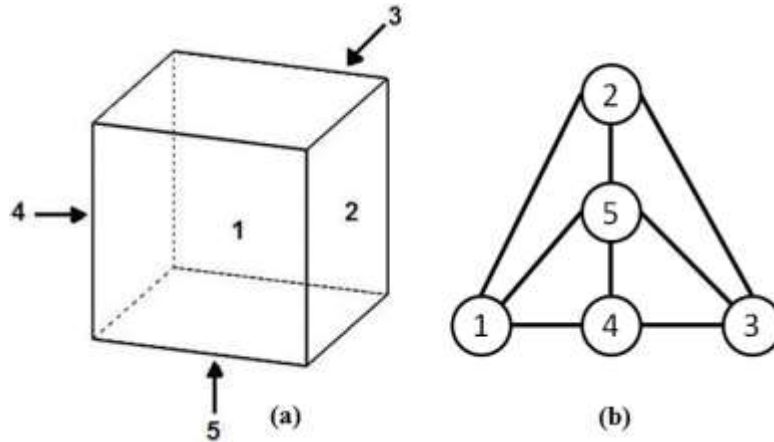
Figure 2.10 (a) Faces of open box structure.(b) FAG for open box.

The generation of spanning trees will be based on changing the location of a -1 entry such that each column (except the fist) has exactly entry of 1 at diagonal cell and entry of -1 elsewhere, such that the summation of each column is zero. For example, the permutations of column 2 in spanning tree matrices extracted from A_{mod} of open box structure are as follow:

$$
\text{Column 2} \quad = \quad
\begin{bmatrix} -1 \\ 1 \\ 0 \\ 0 \\ 0 \end{bmatrix}
\quad \text{or} \quad
\begin{bmatrix} 0 \\ 1 \\ -1 \\ 0 \\ 0 \end{bmatrix}
\quad \text{or} \quad
\begin{bmatrix} 0 \\ 1 \\ 0 \\ 0 \\ -1 \end{bmatrix}
$$

It can be noticed that cell (4, 2) always equals to zero since $A(4,2)=0$, which means there is no such edge that can connect face 4 with face 2. When all columns arrangements are joined together with the different combinations a total of 45 valid spanning trees are produced for structure shown in Figure 2.10, the way to distinguish which combination of the 5 columns produces a valid spanning tree is by inspecting the connectivity of the sub-graph produced by each potential spanning tree, a valid spanning

tree represents a connected graph i.e. all the faces of sheet metal structure is connected with at least one bending edge with other face. For the part in Figure 2.10, there are 108 possible combinations, whereas only 45 of them represent a connected sub-graph. Examples of the 45 generated spanning trees for open box part are listed below in matrix format, and Figure 2.11 shows the graph representation for 9 spanning trees of the open box structure.

$$\text{Spanning Tree 1} = \begin{bmatrix} 1 & -1 & 0 & -1 & -1 \\ 0 & 1 & -1 & 0 & 0 \\ 0 & 0 & 1 & 0 & 0 \\ 0 & 0 & 0 & 1 & 0 \\ 0 & 0 & 0 & 0 & 1 \end{bmatrix}$$

$$\text{Spanning Tree 28} = \begin{bmatrix} 1 & -1 & 0 & 0 & 0 \\ 0 & 1 & -1 & 0 & -1 \\ 0 & 0 & 1 & 0 & 0 \\ 0 & 0 & 0 & 1 & 0 \\ 0 & 0 & 0 & -1 & 1 \end{bmatrix}$$

$$\text{Spanning Tree 40} = \begin{bmatrix} 1 & 0 & 0 & -1 & 0 \\ 0 & 1 & 0 & 0 & 0 \\ 0 & -1 & 1 & 0 & 0 \\ 0 & 0 & -1 & 1 & -1 \\ 0 & 0 & 0 & 0 & 1 \end{bmatrix}$$

The edges that do not appear in a spanning tree are the splitting lines or seam lines, which are broken from the FAG to achieve the flattening process. The established FPEA for sheet metal applications enumerates all possible spanning trees, including the BFT, DFT, and MST(s). The FPEA is equipped with subroutines to produce the DFT and BFT for fast and ready use in cases where one spanning tree of a FAG is enough and the

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study is not concerned with the number of possible 2-D arrangements. Figure 2.12 demonstrates the DFT and BFT generated by FPEA for open box example.

The developed algorithm is considered efficient for applications with small number of nodes as in folded sheet metal application, since the function is exponentially related to the number of links and nodes. Hence the number of possible combinations increase significantly as the number of nodes or/and links of a graph increase.
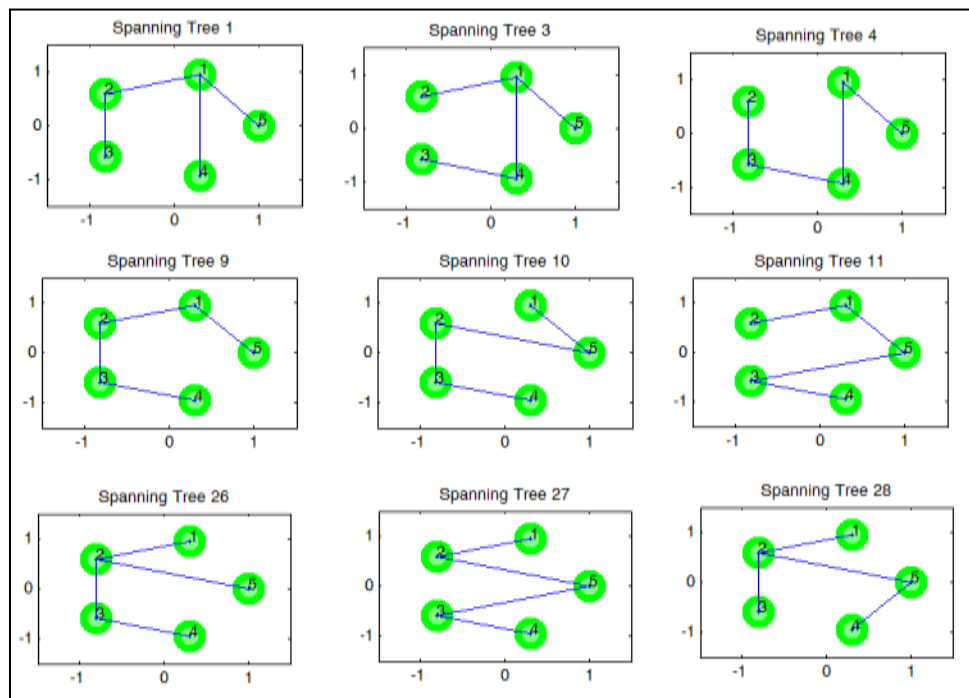
Figure 2.11 Some spanning trees created for flat layouts of open box structure.
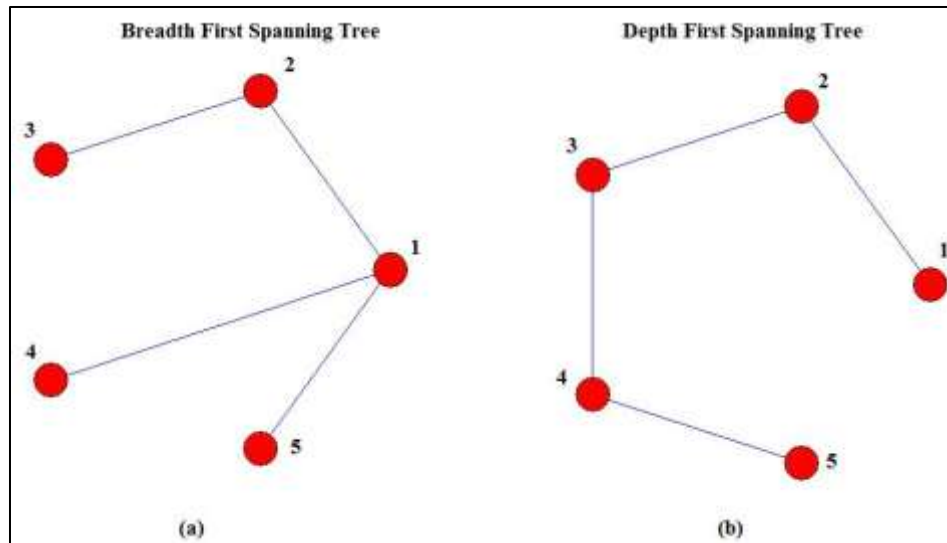
Figure 2.12 (a) BFS tree for open box structure. (b) DFS tree for open box structure.

Flat Pattern Generation

The flat generation process, shown in Figure 2.13, demonstrates the proposed procedure followed in this work to generate the flat layouts. After the FPEA extracts all possible spanning trees of FAG, the next step is to translate the topological findings into geometrical representation. The geometrical information that was extracted from the 3-D CAD file is used in this step to translate each spanning tree into geometrical flattened patterns, where the results of graph traversal phase only conveys the topological permutations possible to link the various faces of a 3-D structure. Nonetheless that information is not sufficient to predict the complete layout of the unfolded flat pattern. Figure 2.14 provides an overall view for the followed steps to generate the flat patterns from 3-D structure in terms of topological and geometrical aspects.

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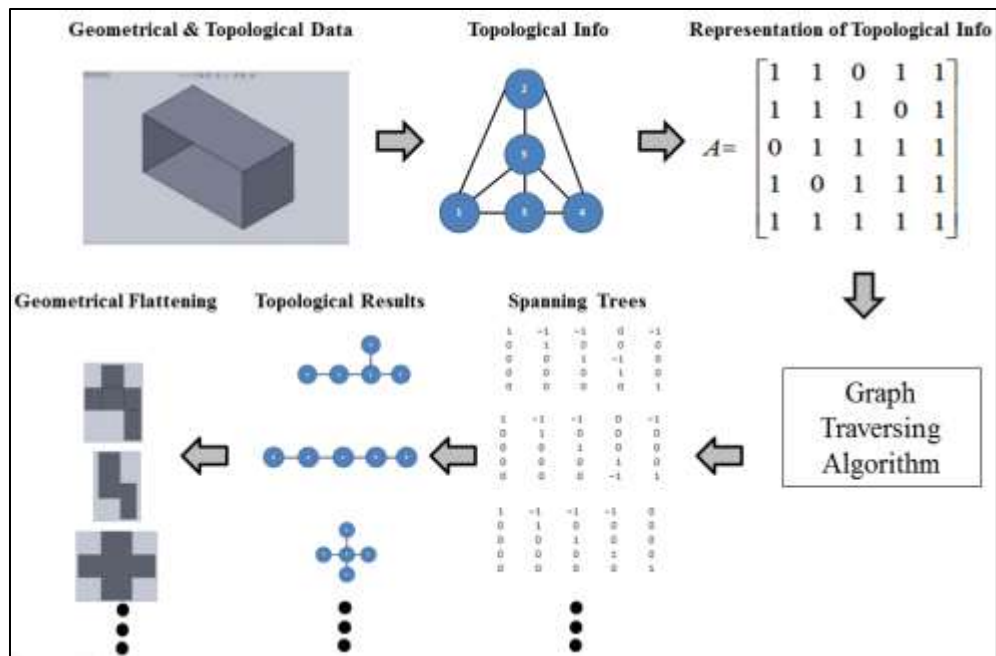
Figure 2.13 Proposed procedure for flat layout generation
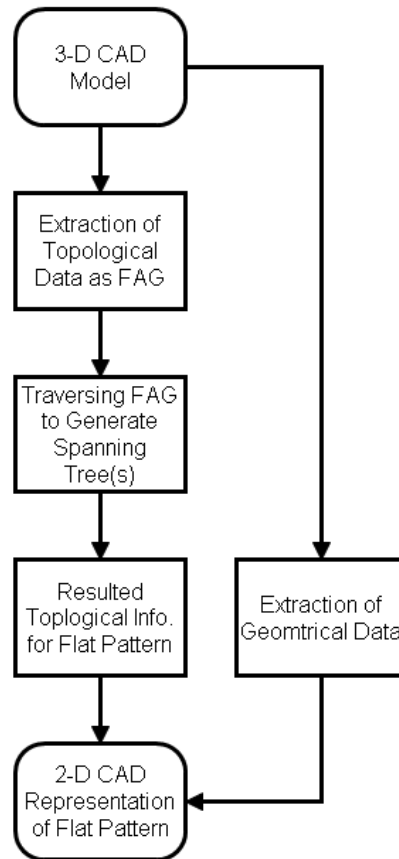
Figure 2.14 An overall view of the procedure followed for flat pattern generation.

The topological data that describe which face are connected in the 2-D pattern is produced by creating the spanning trees of the FAG, nevertheless this data cannot be used alone to generate the 2-D layouts of the metal sheet part, geometric information is needed to translate the spanning trees into faces, edges and vertices with(x, y, z) coordinates. The flatting process employs the information stored in the bending arrangement, or in our case the spanning trees, and projects it on the part geometry. The general steps for flattening can be classified into main six general steps, Figure 2.15. Firstly, selection of a root face from which the analysis will be launched, this also can be the same as the

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source node from which the graph traversing begins. Approaches followed in manufacturing to reduce bending complexity set a root face as the one with largest area or the one with most edges. Secondly, determination of a 2-D reference plane to which all faces will be rotated; the assortment of such plane can be the same as the plane of the root face or one of the main Cartesians planes (xy, xz, yz). The difference between the two options is that in first technique the faces have to be rotated in 3-D every time a new spanning tree is analyzed, however in the case of Cartesian planes all faces are 3-D rotated once and when a new spanning tree is symbolized, the 2-D rotation is needed.
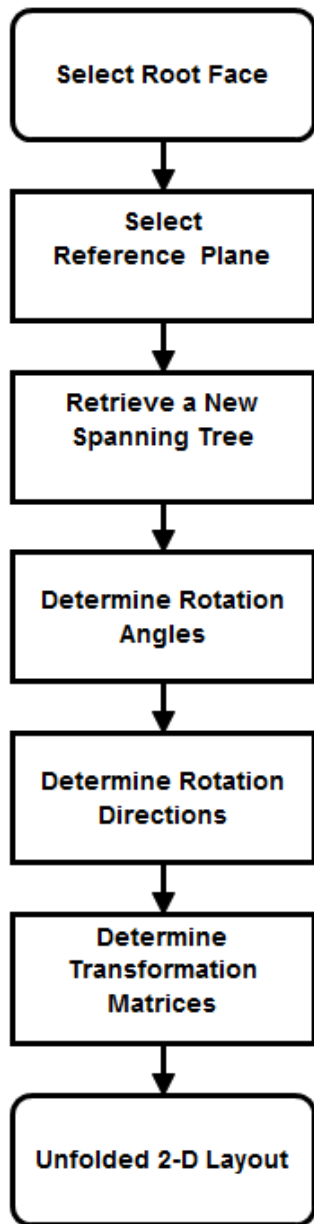
Figure 2.15 General steps for flattening procedure.

Thirdly, evaluation of the rotating angle θ_{ij}, where the angle between two faces i and j is calculated using the normal vectors of the two faces under evaluation. Fourthly, the procedure evaluates the rotating direction, denoted by D_{ij}, for face i with respect to face j by classifying each of the common edges included in the bending arrangement as concave or convex edge relative to the face under evaluation. The sequence of studying faces starts with the root face i and then all faces connected to it i.e. the ith row in the spanning tree, then to other faces directly connected to face i neighbors and so forth. Lastly, technique generates the transformation matrix for each face based on θ_{ij} and D_{ij}.

The formed transformation matrix is used to determine the new coordinates for each faces after rotation; this produces a flat pattern in 2-D world that has the same dimensions of the 3-D folded structure but with different bending arrangement.

2.5   Summary

This chapter discussed a developed systematic procedure to generate flat patterns for a 3-D folded structure called in this dissertation as FPA. The representation principles and constraints to model 3-D folded sheet metal products and their 2-D flat layouts are set, whereas the followed phase included the topological analysis of the structure. This can be done by modeling the topological information of a 3-D folded geometry as a planar undirected graph. Afterwards, the analysis carries the determination of required weld or seam lines needed to be broken in order to unfold the geometry understudy. This is beneficial from manufacturing point of view, since it determines the expected welding or joining load required for the component under study.

The chapter also investigated the employment of graph traversal algorithms for folded sheet metal applications. The graph traversal algorithms enable the FPA to search for valid flat patterns efficiently. Conversely, the type of routine used to conduct analysis, for applications such as folded sheet metal products, affects the final part's design in terms of manufacturing and cost. This is due to differences in resulted bending arrangement that exhibits dissimilarities in subsequent operations as bending and welding or joining. This work developed a FPA system to extract the geometrical and topological information of a 3-D CAD model. Next, a number of graph traversal algorithms are implemented to tackle the same part and highlights the feasibility of each algorithm.

Moreover, the FPA tool included a developed algorithm to enumerate all possible spanning trees by means of permutation, followed by a stage include the geometrical data and generate the flatten layouts , which corresponds to each enumerated spanning tree.

CHAPTER THREE

OPTIMIZATION METRICS FOR FOLDED SHEET METAL PARTS DESIGN

3.1   Introduction

Once all potential 2-D layouts are generated it should be investigated based on a set of optimality metrics that reflect parameters under concern such as manufacturing complexity and cost. The variation between the generated flat layouts is due mainly to its topological differences as expressed by the diverse possible bending arrangements. This chapter discusses the developed set of optimization metrics for folded sheet metal products.

Afterwards all the potential flat patterns are generated for the required 3-D structure, it should be judged based on a set of optimality metrics, knowing that the variations between the 2-D designs are due to change in the faces' orientation relative to a reference face and the location of fold lines (connecting links). The location of fold lines refers to which faces are to be connected to each other along a fold line. The layouts can then be seen as variations of the topological representation for the geometrical shape of the 3-D part, thus the topological data describe the connectivity between the faces and the geometrical shape. Still there is a need to establish selection criteria to favorably choose the best layout among all possible options. The following section proposes a set of optimization metrics for folded sheet metal products.

3.2 Optimality Based on Compactness

Packaging applications relied on compactness to be main selection criteria or optimality measure, especially in paperboards supporting structures. For folded sheet metal application, Compactness Metric (CM) can be considered a major metric for optimized flat layout. This study specifies four measures to quantify compactness of a sheet metal flat layout. Liu et al. (2007) defined optimality criteria for flat patterns where a single-piece layout needed to be as compact as possible. Since compactness of a flat layout can be defined in multiple of ways, this study computes compactness in terms of four different measures. The first terms is the geometric compactness of a flat layout that equals to the ratio of the area to the square of the perimeter (Wang 1997b);

$$CM_{Geometric} = \frac{A}{p^2} \qquad (3.1)$$

Where A is the area of a flat layout, p is the perimeter of the flat layout.

The second measure is based on computing the minimum extent in a certain direction as x-direction or y-direction, or an overall extent considering both x-direction and y-direction. This aspect measures the length of a pattern in one direction; either in x-direction or y-direction. The term requires a zero coordinate to be assigned on the layout perimeter, and then the x-extent is used to represent the difference between the largest and the smallest x-coordinates for all vertices of the graph and so forth for the y-direction. Equations (3.2) to (3.4) calculate the previous aspect. This measure can be essential, when certain restrictions on length in one coordinate exist especially for material handling logistics or for material widths as the case in sheet metal applications.

$$CM_{Min.Extent\ in\ x} = (\ x_i - x_0\ ) \qquad (3.2)$$

$$CM_{Min.Extent\ in\ y} = (\ y_i - y_0\ ) \qquad\qquad (3.3)$$

$$CM_{Min.Overall\ Extent} = \max\ [(\ x_i - x_0\ ), (\ y_i - y_0)] \qquad (3.4)$$

Where, x_i, y_i, x_0 and y_0 are the largest x-coordinate, largest y-coordinate, smallest x-coordinate, and smallest y-coordinate of all vertices in a single flat layout, respectively. Thirdly, the study computes the minimum enclosing area as defined by the smallest rectangular area that encloses the pattern completely, knowing that multiplying the x-extent by the y-extent yields the minimum enclosing area of a layout as indicated in Equation (3.5).

$$CM_{Min.Enclosing\ Area} = (\ x_i - x_0\ )(\ y_i - y_0\ ) \qquad\qquad (3.5)$$

The last measure points out the condensation of flat layout surface by measuring the percentage between the surface area of a flat layout *A* and its enclosing area as shown in Equation (3.6).

$$CM_{Area\ Condensation} = \frac{A}{(\ x_i - x_0\ )(\ y_i - y_0\ )} \qquad\qquad (3.6)$$

This study evaluates each of the compactness four measures separately, to examine all the generated flat patterns. Then, the results define four optimal layouts each corresponding to a different criterion. In addition, it is possible to have the same optimal flat pattern selected for more than one measure. Figure 3.1 shows the optimal flat patterns for a 3-D structure, selected based on the discussed four compactness measures. For folded sheet metal applications, the part 2-D layout will be cut from a metal strip, where copies of the selected patterns are arranged along the stripe to be laser cut or punched. Hence the optimal flat pattern, which achieves the best arrangement over a contained region of a stock, cannot be readily determined from the compactness measures alone.

Consequently, the next section discusses the developed measures for manufacturability and material utilization.
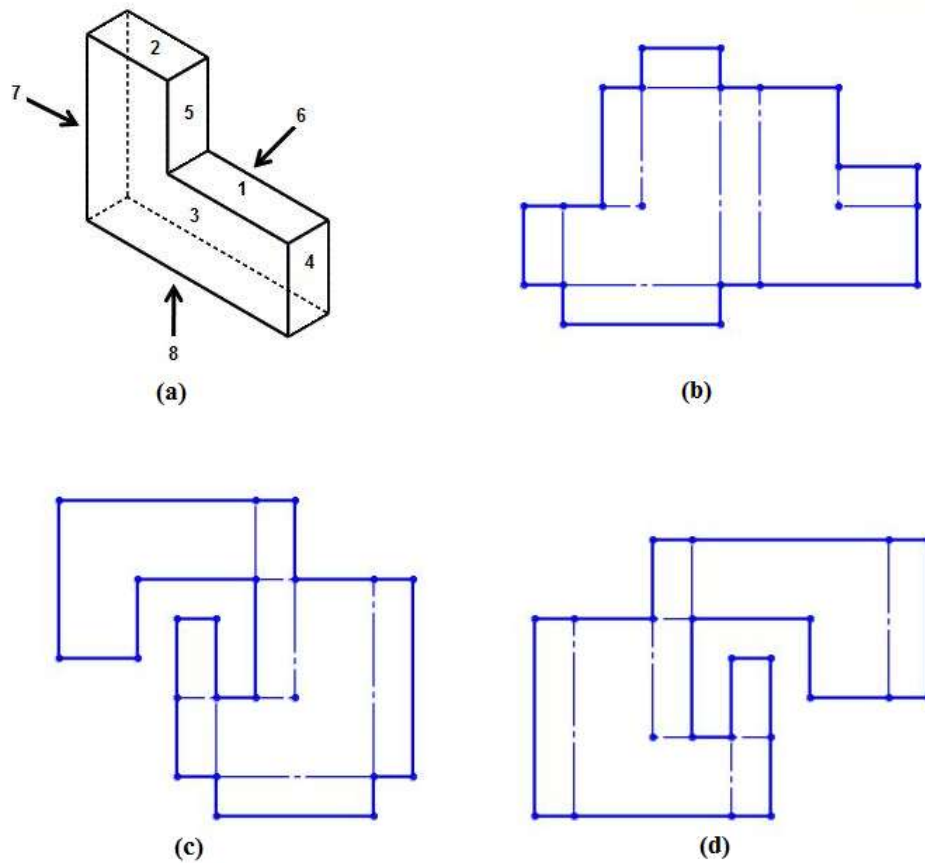
Figure 3.1 (a) 3-D part with 6 faces. (b) Most geometrically compact and most area condensed layout. (c) Minimal overall extent layout. (d) Minimal enclosing area layout

3.3   Optimality Based on Nesting Efficiency

Nesting problems for regular and irregular shapes were formulated in published literature as an optimization problem with an objective concerned with the maximization of the utilized material or alternatively the minimization of generated engineering scrap.

The metal coils from which the flat layouts are produced come with certain widths and thicknesses from the steel mills. Table 3.1 lists the width and thickness ranges for coils of different commercially available steel grades.

Table 3.1 Width and thickness ranges for a group of steel grades

Material	SAE Class	Grade		Width Range (mm)	Thickness (mm)
		SAE	AISI		
HR	SAE J2329	1	CQ	610-1829	1.00-9.53
HR	SAE J2329	2	DQ	610-1829	1.00-9.53
HR	SAE J2329	3	DDQ	610-1829	1.00-9.53
CR	SAE J2329	1	CQ	610-1829	0.38-3.30
CR	SAE J2329	2	DQ	610-1829	0.38-3.30
CR	SAE J2329	3	DQ	610-1829	0.38-3.30
CR	SAE J2329	4	DDQ	610-1829	0.38-3.30
CR	SAE J2329	5	EDDQ	610-1829	0.38-3.30
CR	SAE J2340	180 A	Dent Resist	610-1829	0.64-2.79
CR	SAE J2340	210 A	Dent Resist	610-1829	0.64-2.79
CR	SAE J2340	250 A	Dent Resist	610-1829	0.64-2.79
CR	SAE J2340	280 A	Dent Resist	610-1829	0.64-2.79
CR	SAE J2340	300 X	HSLA	610-1524	0.76-3.18
CR	SAE J2340	301 X	HSLA	610-1524	0.76-3.18
CR	SAE J2340	302 Y	HSLA	610-1524	0.76-3.18

Consequently, an optimality measure should be developed to check for width restriction on the pattern geometry when it is created from a strip with W width; Such that the maximum extent of a pattern's layout in width direction should not exceed W. This restriction for optimal nesting design should consider; (i) the pattern orientation with respect to a fixed coordinate on the strip, (ii) the number of patterns or copies to be created from one strip and their corresponding arrangement, and (iii) the number of

pattern designs to be created; with the goal that more than one part is to be produced from the same strip. These three aspects are necessary to increase material utilization. The width restriction is expressed in Equation (3.7).

$$n_1 (D_{i1} - D_{01}) + n_2 (D_{i2} - D_{02}) + ... + n_k (D_{ik} - D_{0k}) + C \leq W \qquad (3.7)$$

Where n_k is the number of flat layouts arranged in width direction W for part k. D_{ik} is the largest coordinate for the flat layout k in W direction, and D_{0k} is the smallest coordinate. C all allowance distances between patterns on the strip. Figure 3.2 illustrates the variations in pattern's maximum extent due to its orientation over a strip with width W.
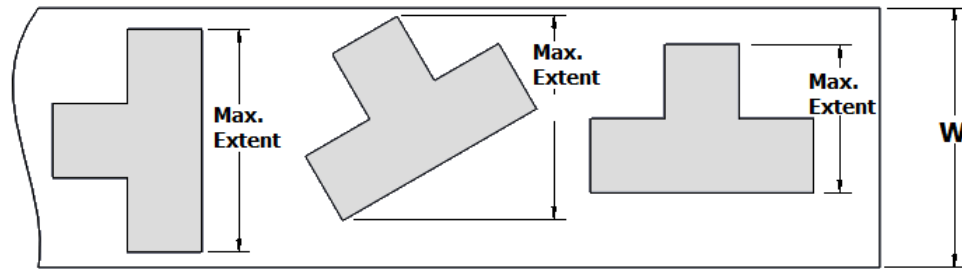
Figure 3.2 Maximum extent variations due to pattern orientation; Strip width W

For flat patterns arrangement, it is important to consider designing multiple copies in a contained region of sheet metal with no overlapping. Thusly, the nesting efficiency should also be used to help define the optimal flat pattern layout for the specific 3-D structure. Nesting is defined in terms of the percentage of materials utilization, i.e. the least material scrap. In this work, a nesting efficiency of 70% to 80% (i.e. material utilization) is set as indication of good nesting following Boljanovic (2004) recommendations. The design of the strip layout is generally described through three key

models that are different in terms of two main dimensions m and n, where m is the distance from the edge of the layout to the side of the strip, and n is the distance between the layouts on the same strip. Figure 3.3 demonstrates the assigned parameters in strip design. Here, the design manipulation is based on deciding on the m and n values. One model uses only the value of n while having $m=0$, the second sets zero values for both, thus $n=0$ and $m=0$. While the third model that is used in this work assigns values for m and n greater than zero. These parameters are important because material requirements cannot be calculated unless they are set.
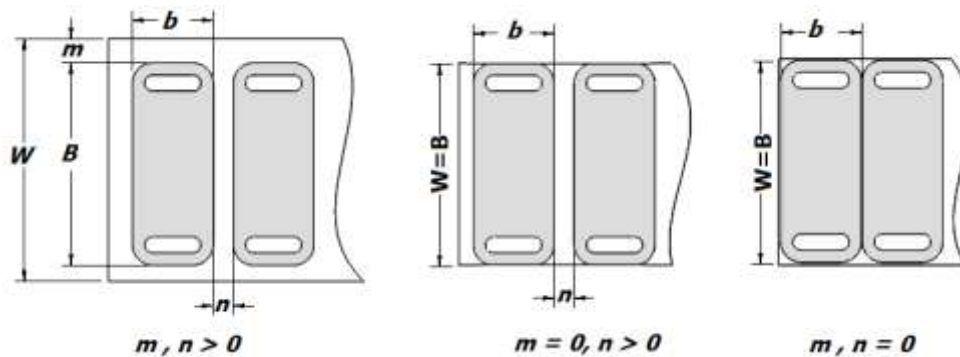
Figure 3.3 Strip scrap model parameters; Strip width W, Layout width B, Layout length b, Distance from the edge of the layout to the side of the strip m, Distance between the layouts n

This study computes m and n based on the coil or material thickness T, its strip width W and the layout width B; per the conditions in Table 3.2; the assigned values for each of the model parameters T, W, m, and n are established based on best practices for nesting found in literature for each investigated thickness and width of sheet metal strip,

the minimum values of *m* and *n* are set to avoid defects such as tearing or cracking when forming or cutting the single-piece of the nested strip.

To evaluate the optimal patterns generated for the L-shape structure shown in Figure 3.1, the material thickness is assumed to be 0.4 mm with a strip width W greater than 610 mm. m is assumed to be 4 mm and n equals 4 mm. The laser cutting operation is proposed to cut the patterns out of the strip, hence tight tolerance can be achieved; laser beam machining process can produce holes as small as 0.005 mm. Moreover, the entire patterns layouts are set to be on the inner faces of the final 3-D part with 0.4 mm thickness that is folded through a sheet metal folding operation with material discontinuities along the bend lines; therefore no bending allowance is taken into consideration.

Table 3.2 Values of *m* and *n* in strip design model for each strip thickness and width

Strip Thickness T (mm)	Strip Width W (mm)	Value of *m* (mm)	Value of *n* (mm)
T ≤ 0.6	W ≤ 75	2.0	2.0
	76 ≤ W ≤ 100	3.0	3.0
	101 ≤ W ≤ 150	3.5	3.5
	151 ≤ W	4.0	4.0
0.61 ≤ T ≤ 0.8	Any value of W	$m = T + 0.015\ B$	3.5
0.81 ≤ T ≤ 1.25			4.3
1.26 ≤ T ≤ 2.5			5.5
2.6 ≤ T ≤ 4.0			6.0
4.1 ≤ T ≤ 6.0			7.0

When conducting nesting for folded sheet metal parts there are multiple flat layouts designs to consider which all can be folded to the same 3-D structure. However, the outcome obtained by applying compactness metric cannot be considered explicitly to achieve the best arrangement over a contained region of a stock, since the 2-D patterns are evaluated as single-piece layouts. This does not indicate that the nesting and compactness measures are not strongly linked in folded sheet metal application. Nevertheless, in this analysis the Nesting Efficiency Metric (NEM) utilizes the compactness measures as initial inputs for further investigation with respect to nested material utilization percentage, which can be measured as total area of cut layouts divided by total area of metal strip used. NEM for a flat layout in folded sheet metal applications is given in Equation (3.8)

$$NEM = \frac{nA}{LW} \qquad\qquad (3.8)$$

Where A is the surface area of a flat layout, n is the number of flat layouts cut from the strip. W is strip width. L is the total length of strip used to produce the flat layouts.

To set the orientation of flat layouts for nesting a heuristic approach is used. Illustration of the approach is given in Figure 3.4 to calculate NEM for each flat layout.

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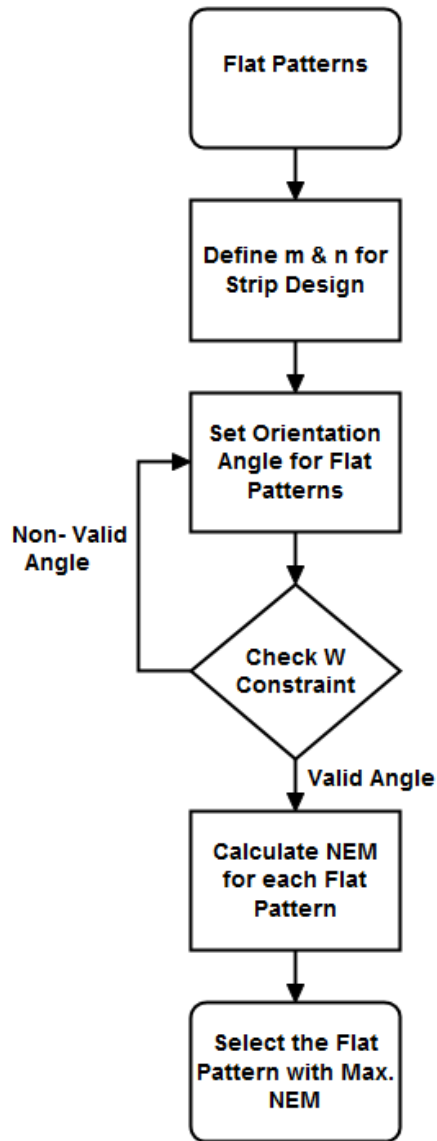
Figure 3.4 Steps to determine NEM for flat patterns.

Evaluating the optimal patterns of an L-shape structure in terms NEM yields 76% utilization for two patterns, those are the most geometrically compact and the minimum overall extent, whereas their single-layouts have an efficiency of 65.7% and 63.8% respectively. Lastly, the minimum enclosing area layout scored 71% for NEM compared to 65.7% for a single-layout. Figure 3.5 shows the designed arrangements for each

optimal layout. It can be seen that evaluating the generated flat patterns in terms of nesting efficiency produces better final selections for flat patterns of sheet metal fold forming process.
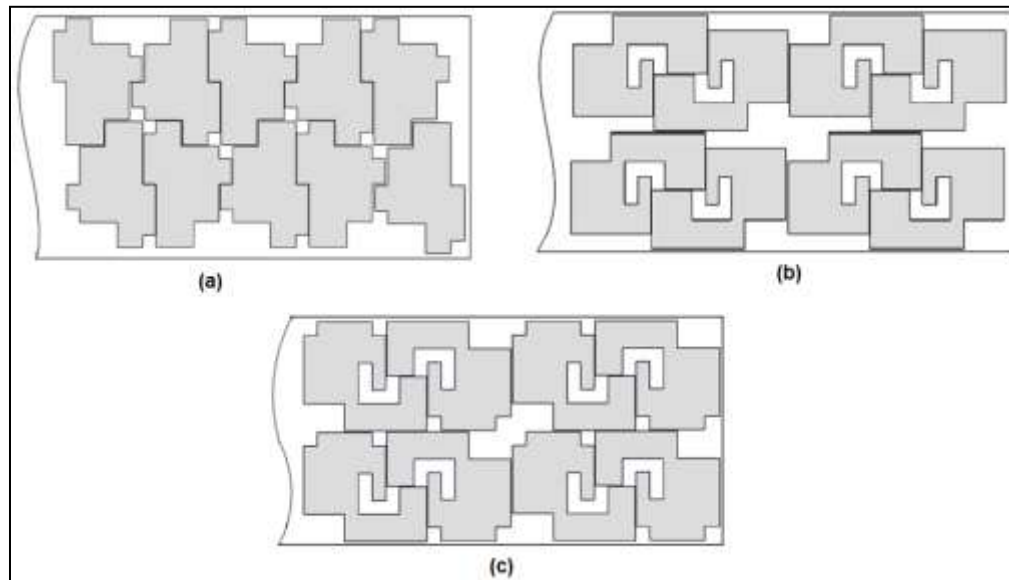
Figure 3.5 Nesting arrangements for optimal layouts: (a) most geometrically compact pattern & most area condensation: single layout utilization (65.7%), NEM (76%). (b) Minimum overall extent pattern: single layout utilization (63.8%), NEM (76%). (c) Minimum enclosing area: single layout utilization (65.7%), NEM (71%)

3.4   Optimality Based on the Number of Bend Lines

This study will also evaluate the developed flat patterns based on the number of bend lines located in the 2-D layout to be folded to the desired 3-D structure. This is essential from the folding-process wise, where the folding operations require the minimum number of folding steps.

To check for the number of bends or fold lines, the Number of Bends Metric (NBM) is used to validate the representation of a sheet metal product from topological point of view. For each selected flat pattern, the NBM is computed by Equation (3.9);

$$NBM = f - s - e + v + g_{nm} - m \qquad (3.9)$$

Where, f is number facets, s is number components, e is the number of free edges, V is the number of vertices, g_{nm} is the number of non-intersecting closed curves, m is the number of enclosed volumes. The results from Equation (3.9) compare between the different part designs (i.e. flat patterns among more than one design of a part) while validating the generated flat patterns topology.

3.5   Optimality Based on Bend Lines Orientation

The last manufacturability driven optimality measure, proposed in this work, is based on the bend lines' orientation. Earlier works discussed the development of robotic arms to fold origami paper and carton products as in Balkcom et al. (2004), Tanaka et al. (2007) and Yao et al. (2011). However, for folded sheet metal applications, robotic arms can be utilized to fold the part over the bend lines in a sequential manner; hence the process sequence and precedence must be considered when designing a flat pattern for a folded part, to accommodate the process capabilities – in terms of equipment- and time constraints.

The bend lines orientation with respect to a robotic arm direction affects the operational steps for the folding procedure, where the part orientation needs to be adjusted after each bending operation to enable accurate folding. Bend lines with different orientations demand more adjustment steps either for the part or the robotic

end–effecter; hence a flat pattern design with less variation in its bend-lines' orientations can lead to better process performance. This practice can be followed for folded sheet metal parts to ensure accurate sequential bending operation. The Orientation of Bends Metric (OBM) can be defined by computing the maximum number of bend lines that match directions of any arbitrary chosen axis as x or y, or located in xy plane for each 2-D layout as shown in Equation (3.10). Subsequently, the flat pattern with maximum OBM can be selected while the direction of robotic end–effecter can be set to coincide with the direction of greatest OBM.

$$OBM_{axis} = \max(n_x, n_y) \hspace{3cm} (3.10)$$

Where, n_x is number of bend lines parallel to the x direction. n_y is number of bend lines parallel to the y direction.

Future aspect to be explored in terms of the processing is the sequence of the bending operation, which corresponds to each flat pattern. Figure 3.14 illustrates the bend lines orientation for the L-shaped part.
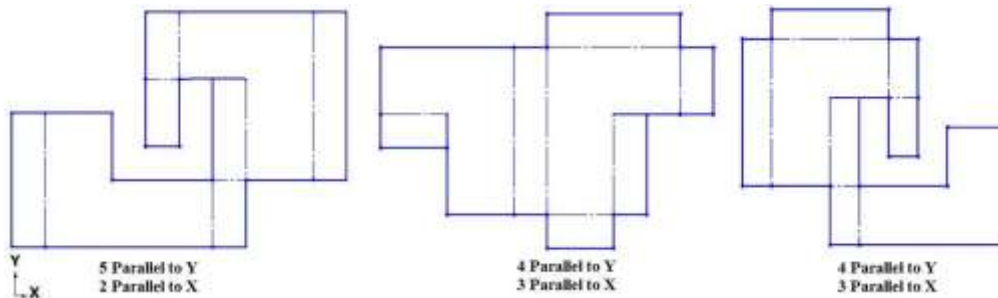
Figure 3.6 Evaluating flat patterns based on bend lines orientations

3.6   Optimality Based on Welding Cost

In previous chapter, we discussed the optimization of flat pattern profile based on total welding cost. Nonetheless, this step was discussed during the graph traversal algorithm where no geometrical information still known within the spanning trees. This can be explained by the fact that Prim's algorithm that was employed to generate MST is concerned with the linking edges of a FAG, while adding the WFAG to the calculation is sufficient to account for the length of each edge. Therefore, the minimum Welding Cost Metric (WCM) can be calculated by Equation 3.11 as follows:

$$WCM = \sum_{1}^{k} W_{i\,(MST)} \qquad (3.11)$$

Where, $W_{i(MST)}$ the weight assigned for edge i in the minimum spanning tree. k is the total number of edges in a spanning tree.

3.7   Validation of Optimization Metrics

All the aforementioned metrics can be used to select one flat pattern that satisfies at least one optimization need for a specific design, hence reducing the number of possible flat patterns options to one or two. In order to investigate the validity of the established metrics; three examples of folded sheet metal parts are examined. The only available optimization metrics in literature for folded geometries are used in packaging industry to validate folded structures of carton and are mainly based on compactness measures. However, in cases of folded sheet metal structures the design and process needs require different scopes of selection criteria for the flat pattern layout.

3.7.1 Example-1

The first example is a joggle, which is a common sheet metal part with 7 faces and 10 total links; Figure 3.7 shows the 3-D geometry of Example-1 along with its FAG representation. The joggle is a non-convex and non-manifold structure that possesses faces in inclined position to the neighbored faces; specifically feces 2 and 5. These faces are anticipated to cause overlapping issues in the flat pattern of the 3-D structure. Running the FPA for that structure generates 64 total spanning trees, where only 4 of them can practically produce a flat pattern as a result of violation of geometrical constraints (i.e. overlapping between faces in the excluded 60 spanning trees). Figure 3.8 lists the 4 generated flat layouts for Example-1.
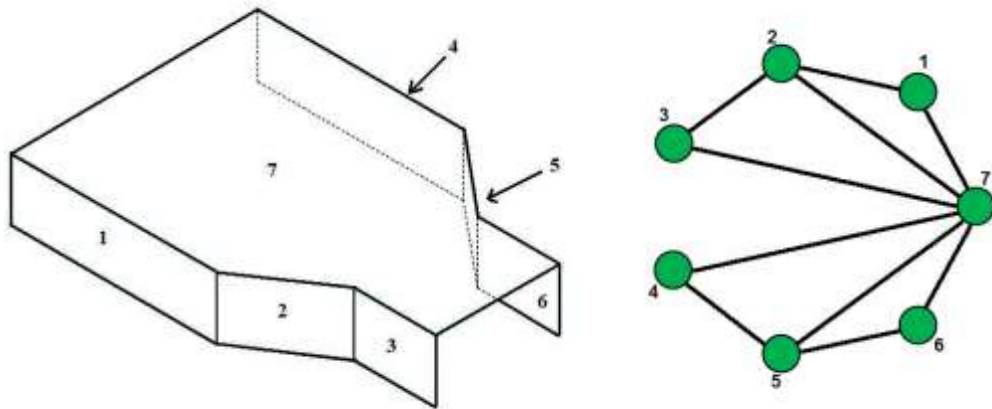
Figure 3.7 Structure of Example-1 and its FAG.
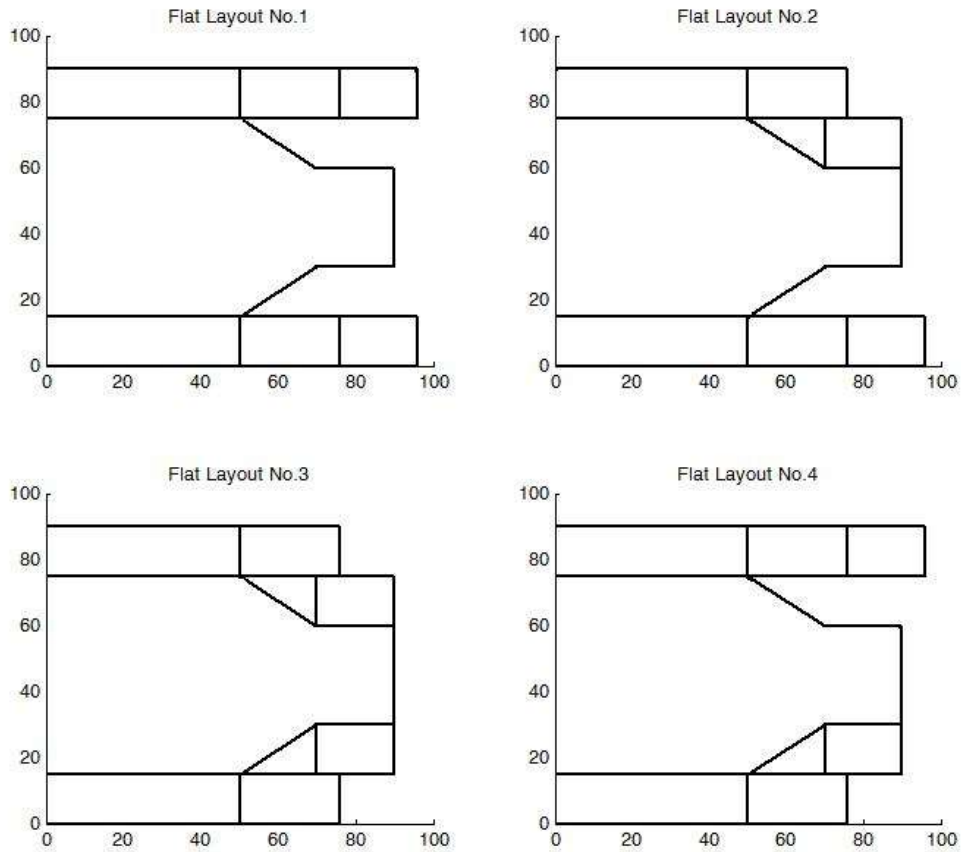
Figure 3.8 Valid flat layouts for Example-1.

The proposed optimization metrics are implemented to select a single design of a flat pattern to be manufactured and folded into the final 3-D joggle. The results for each metric are listed in Table 3.3. All compactness measures ($CM_{Geometric}$, $CM_{min.OverallExtent}$, $CM_{min.EnclosingArea}$, and $CM_{Area\ Condensation}$) select flat layout number 3, shown in Figure 3.8 as the most optimized 2-D layout in terms of compactness. In addition, NEM indicates the same flat pattern as the most optimized one in terms of nesting efficiency. However, NBM specifies equal values for all flat patterns. While, OBM highlights flat layouts 1 and 3 as the most optimized designs in terms of bends' orientation. The proposed metrics

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analyze the flat layouts in terms of different objectives and point out flat layout number 1 as being optimal with respect to OBM, in addition to flat layout number 3 that is common among all.

3.7.2   Example-2

Example-2 represents a non-manifold L-shape structure made of folded sheet metal with 6 faces and 10 total links. Figure 3.9 shows Example-2 and its FAG. The number of possible spanning trees is 128, however only 12 of them stand for valid flat layouts, shown in Figure 3.10.
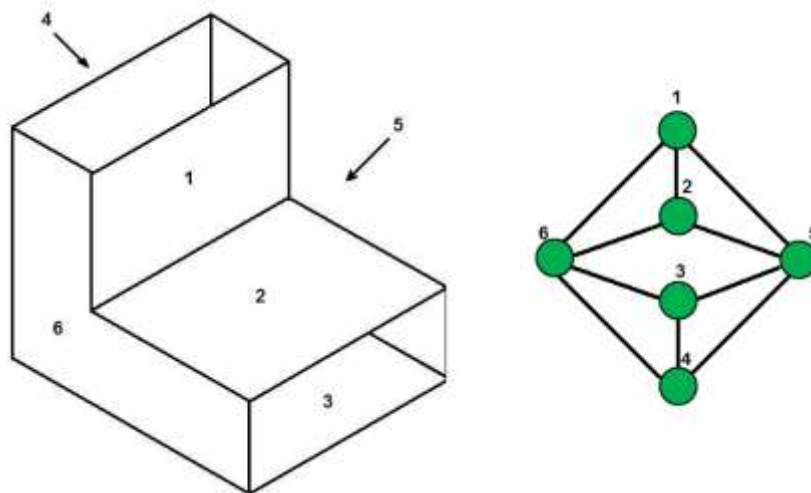
Figure 3.9 Structure of Example-2 and its FAG.
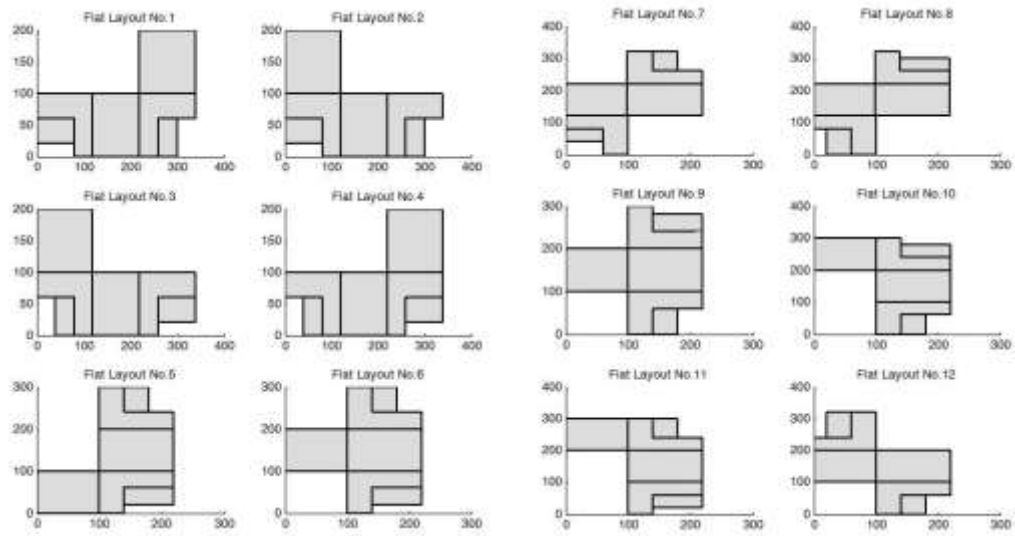
Figure 3.10 Valid flat layouts for Example-2.

The compactness criteria select the flat layouts 1, 2, 3 and 4 as the most optimized designs in terms of compactness, Table 3.3. However, NEM nominates flat layouts 10 and 12 to achieve the most optimized flat patterns designs in terms of nesting efficiency. NBM specifies equality for all flat layouts in terms of number of bend lines. While OBM selects flat layouts 7 and 8 as the most optimized designs for a flat pattern of L-shape structure. The results demonstrate differences in selected pattern with no common flat layout among metrics, though for CM the resulted designs are common between the various branches of CM.

3.7.3 Example-3

Finally, Example-3 represents a metal enclosure with 4 faces and 5 connections, displayed in Figure 3.11. The examination of the spanning trees indicates a total of 8 spanning trees of the FAG and all of these trees can produce valid flat layouts, Figure 3.12 lists the possible flat layouts of Example-3.

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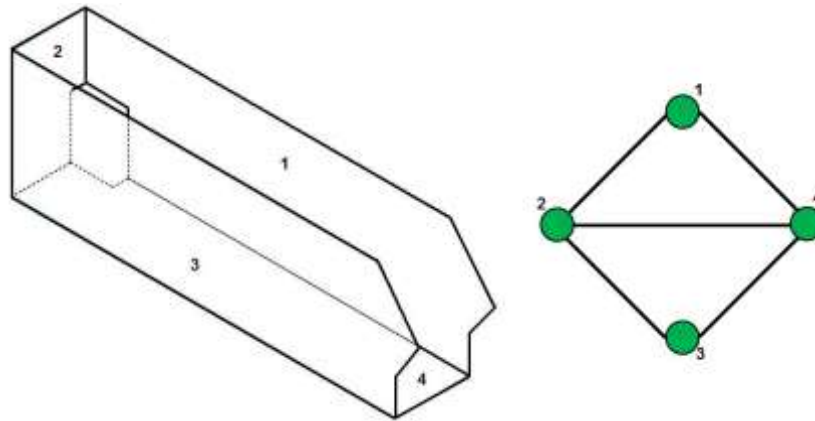
Figure 3.11 Structure of Example-3 and its FAG.
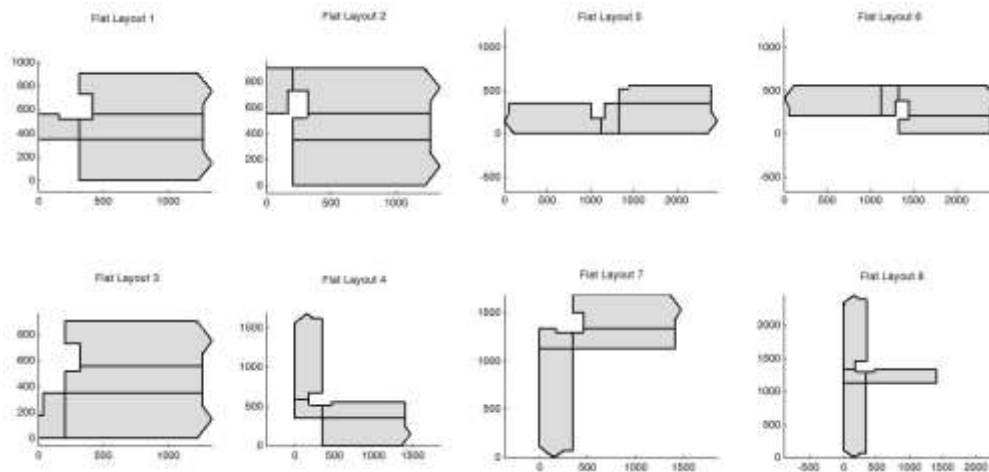
Figure 3.12 Valid flat layouts for Example-3.

The outcomes from Example-3 point out flat layout 2 and 3 to be the most compact design in terms of $CM_{min.OverallExtent}$, $CM_{min.EnclosingArea}$ and $CM_{Area\ Condensation}$. Nevertheless, $CM_{Geometric}$ indicates flat layout 3 only as the optimized flat pattern. On the other hand, NEM selects flat layout 5 and 6 as the most optimized pattern designs for metal enclosure from nesting point of view. The remaining metrics, NBM and OBM, find all flat layouts equal in terms of number and orientation of bend lines.

The results of the optimization metrics for all of the three examples are listed in Table 3.3. The first three columns indicate information about the structure of each example, as number of faces and number of links. The results of FPA are listed in columns 4 and 5, where the number of generated spanning trees is listed along with the number of valid layouts after applying overlapping detection. The rest of Table 3.3 content presents the results for each optimization metric; the optimized flat layout design for each metric is highlighted.

It can be seen that the NBM value is constant among the flat patterns that correspond to one part design; this metric is beneficial to favorably decide on different part modifications during design phase. The results indicated that the developed metrics are able to convey new design objectives in the optimization process when selecting a flat pattern. The designer can favorably choose based on the major optimization target under concern. For example, if the designer is dealing with the part in Example-2 and the optimization goal under concern is to design a flat pattern with minimum scrap reduction, then the designer needs to select flat layout design 10 or 12. Conversely, if the optimization target is more focused on orientation of bend lines due to limitation in machinery capability, then flat layout design 7 or 8 is the best one to select. And if compactness is the essential criterion that controls the design, then the designer will have flat layout designs 1, 2, 3 and 4 to consider as the best designs that offer most compacted 2-D layout for the part. Moreover, within the compactness optimization target, the designer need to identify the best measure for compactness that expresses the parts

features under concern. This work offers three adopted metrics from packaging application in addition to the area condensation metric, which is developed in this work.

The results of the three examples showed that the developed metrics selected different flat layout designs to generate the final 3-D part by folding; this is a result of the different optimization goals each metric satisfies. It can be seen that the compactness measures are not always able to select the flat layouts that perform best during nesting even though the compactness measures focus on area aspects. Therefore, the arrangement of multiple flat patterns over a stock of material, indicated by NEM, lead to different flat layout designs. In addition, the area condensation metric is capable of measuring the material utilization performance of a flat layout if one pattern is to be cut out of a rectangular metal strip. However, this is not the case in manufacturing, where multiples of the patterns are arranged over the same metal strip.

NBM is constant for one 3-D part design, which means that the metric is not valid for optimization among the flat patterns of the same 3-D part. Yet, its validity is demonstrated when different designs of 3-D parts are compared. The OBM results highlighted flat patterns designs that incorporated machinery capabilities and bends' orientation; this can lead to flat pattern designs that are not necessarily optimized in terms of CM and NEM. Therefore, the selection of optimization metric requires defining the most manufacturing aspect that the flat pattern must accommodate, however the results showed that it is possible to have one flat layout that scores the best in terms of most of the optimization metrics, such as flat layout 3 in Example-1. The importance of each metrics can be determined based on the designer's needs and the limitations in the

process and machinery, afterwards the designer selects the optimization metrics that best serves those needs and limitations. Yet, for folded sheet metal parts the nesting efficiency is generally the parameter under major concern.

Table 3.3 Results of optimization metrics for examples 1, 2 & 3

EX.	CM Geometric	CM min.OverallExtent	CM min.EnclosingArea	CM Area Condensation	NEM	NBM	OBM	WCM
1	Layout (3)	Layout (3)	Layout (3)	Layout (3)	Layout (3)	All equal; 6 bends	Layout (1),(3)	Layout (3)
2	Layout (1),(2), (3),(4)	Layout (1),(2), (3),(4)	Layout (1),(2), (3),(4)	Layout (1),(2), (3),(4)	Layout (10),(12)	All equal; 5 bends	Layout (7),(8)	Layout (3),(4)
3	Layout (3)	Layout (2), (3)	Layout (2), (3)	Layout (2), (3)	Layout (5),(6)	All equal; 3 bends	All equal	Layout (3)

3.8   Summary

The established optimization metrics for folded sheet metal products are discussed in details in this chapter. The development of manufacturing and cost based metrics is essential as a subsequent step for FPA, since it limits the number of feasible flat patterns to few candidates that takes into consideration the manufacturing needs of folded sheet metal products and the fold forming process, such as the compactness metrics that considers the geometrical dimensions of a flat pattern in terms of four measures, nesting efficiency, total welding cost, number of bend lines, and orientation of bend lines. Each of the metrics represents a requirement product or process wise.

In conclusion, the developed metrics provided broader analysis space for flat patterns other than the traditional measure that only translate the compactness need as the main judging factor. The optimization metrics are indices to select best flat pattern design among all generated ones for one specific 3-D structure. Therefore, the metrics may select different flat layouts to be the most optimized one since the selection objective is not the same.

CHAPTER FOUR

STRESS-BASED RANKING OF FOLDED SHEET METAL DESIGN

4.1   Introduction

The previous chapters discussed the topological aspect and the geometrical optimization of a folded sheet metal part, however there is a mechanical performance aspect of each folded sheet metal component that needs to be taken into consideration. In the design of folded sheet metal parts, an important issue to be discussed is the significance of such flat pattern design on its final stressed-based performance under specific applied loading conditions.

It can be seen from previous analysis that the main parameter leading to the existence of various flat pattern designs, for the same 3-D component, is the different combinations of the folding and the welding lines. During a loading scheme, the 3-D component is anticipated to behave differently for each flat pattern design, this can be explained by the different strength each fold and weld line might retain.

The objective of this chapter is to define an analysis methodology to determine and judge the validity of a flat pattern design by studying stress-based ranking of folding lines. Moreover, to select the most optimized flat pattern design that enhances the initial mechanical performance of the final 3-D component.

4.2   Related Work

The examination of the mechanical characteristics of origami products was not under considerable interest in the literature, since origami science dealt with paper based structures, which served only geometrical and topological needs rather than load bearing requirements. However, when applying origami principles to other types of materials as sheet metallic products, the stressed-based aspect become one of the major parameters that a designer should consider. (Johnson et al. 1980) researched the required work to fold a flat sheet metal part along straight and curved fold lines to produce various surfaces, their analysis assumed inextensibility of the sheet metal material. Their outcome was purely numerical equations that connected the plastic work required with the fold angle, though the work depended heavily on the geometrical and the kinematic analyses for each dimension, in addition to the fact that it was not generic and considered each shape to be unique. On the other hand, Hull (2002) and Watanabe et al. (2006) discussed the rigid foldability of origami by comparing it to a model of metal plates that have hinges instead of creases. However, the study focused on deriving a methodology to judge foldability of origami based on schematic and numerical methods, while no stressed-based performance or characteristics were analyzed.

The flexibility and stiffness of folded textures were also discussed by Schenk et al. (2009) and Schenk & Guest (2011), their study focused on the global mechanical properties of the sheets that can be favorably modified. Their work studied the properties of the sheets using numerical model with the aid of pin-jointed framework modeling to capture the major deformation modes. Though, the folded sheets considered are not

necessarily developable, i.e. there is not necessarily a feasible flat pattern for each folded sheet structure.

Other mechanical application of folded structures discussed for sandwich composite materials, Heimbs et al. (2007) investigated the folded configurations under compression for core structures, the major tool used in the analysis is the dynamic compression test simulation accompanied with experiments. The outcome of the study was a geometry optimization in order to improve mechanical properties with minimum density, yet the analysis covered the compression behavior only.

Other literature handled the manufacturing processes required to fold specific shapes and geometries of folded sheets as in Schenk et al. (2011) work. They worked on introducing a novel approach to fold Miura-ori metallic sheets using cold gas pressure forming, the calculation of forming pressure assumed ideal plastic material model with plastic hinges along the fold line.

4.3   Representation of 3-D Structure

The main importance of the stressed-based ranking for flat patterns can be captured through the representation of the 3-D structure upon folding. In order to investigate the deformation of a part, our approach here is based on modeling the folded state of a folded pattern as a pin-joined truss framework, where each vertex is denoted with a node while each line connecting two nodes is represented as load bearing element (i.e. truss member), Figure 4.1. Distinct fold lines surround the faces and the structure is approximated to be a polygonal facet surface by polygon triangulation, whereas the faces do not bend and the behavior of fold lines is estimated as hinges. The pin-jointed

approximation has been introduced previously for Origami based structures as in the work of Tachi (2006) and Watanabe et al. (2006).

The modeling of 3-D folded sheet metal parts as pin-joints enables the application of structural analysis to determine the axial stress in each of the elements as a result of certain loading scheme.
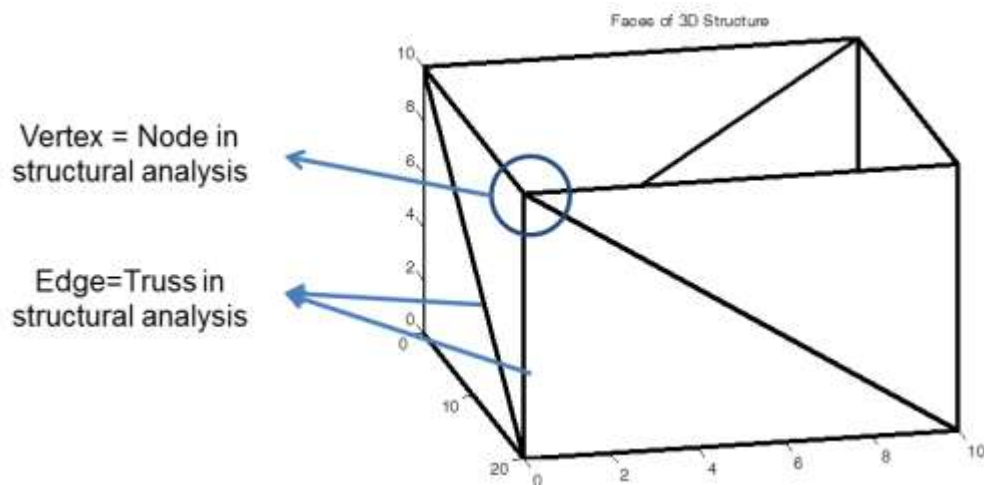
Figure 4.1 Pin-joint modeling of 3-D folded structure

4.4   Structural Analysis

The structural analysis followed in this dissertation depends on the stiffness method, which is considered as an efficient way to solve complex, determinant, and indeterminate structures. The analysis subdivides the structure into discrete elements, and then formulates the individual stiffness matrix for each of those elements. Afterwards, the global matrix of the whole structure is assembled and is transformed to the reduced matrix by applying the boundary conditions of the 3-D structure. Subsequently, the

reduced matrix is inverted and multiplied by the set of applied forces to produce the resulted displacement of structure in terms of nodes. Finally the analysis contains the post-processing step to generate the axial stress in each of the elements.

For a single member, there are two coordinates under concern; the first one is the local coordinates where its individual stiffness matrix is computed; while the second is the global coordinates where the transformation matrix is formulated to transform the local matrices into global coordinates. Figure 4.2 illustrates the local and global coordinates of a truss member, where X-Y are the global coordinates, and X′-Y′ are the local coordinates, θ is the angle between local and coordinate coordinates, *N1*, *N2* are the initial and final nodes. The stiffness matrix of one element can be found using Equation (4.1),

$$k = \frac{AE}{L} \begin{bmatrix} C^2 & CS & -C^2 & -CS \\ CS & S^2 & -CS & -S^2 \\ -C^2 & -CS & C^2 & CS \\ -CS & -S^2 & CS & S^2 \end{bmatrix} \tag{4.1}$$

Where, *A* is the cross section area of the element, *E* is modulus of elasticity, *L* is the length of the member, *C* is cos(θ), *S* is sin(θ), and *K* is the member stiffness matrix.
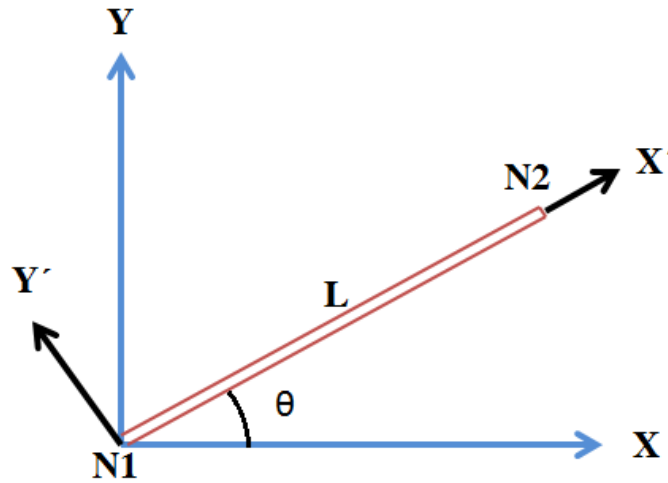
Figure 4.2 Local and global coordinates of a truss member in structural analysis.

The structural analysis calculates the nodal displacement and deformation, in addition to the axial force exerted on each element. This can produce the axial stress applied in elements. Full detailed structural analysis can be found in (Kassimali 1999).

4.5   Modeling of Flat Patterns for Stressed-Based Ranking

The application of structural analysis for flat pattern requires modification for the types of elements, so it can accommodate the different combinations of the fold and weld lines. For each of those lines, the stressed-based capabilities are different as a result of material discontinuities that distributed along the fold lines and the alteration of material at the weld lines. Therefore, to optimize the flat pattern in terms of its stress-based behavior each type of lines in structure should have a parameter that defines its type. According to the polygonal approximation we have three different kinds of lines; those are fold lines that represent debilitated line due to material discontinuities, a weld line with altered material due to welding process, and a face line which represents the actual

strength for the 3-D structure material since no processing or material removal occurs at face level. Figure 4.3 indicates open box structure and its representation in terms of the three types of elements.

The classification of lines serves to distinguish the flat patterns in terms of their stress-based behavior, if the flat pattern shown in figure 4.3 (b) is used to fold the open box geometry, then the combination of fold, weld and face lines are represented in Figure 4.3(a).
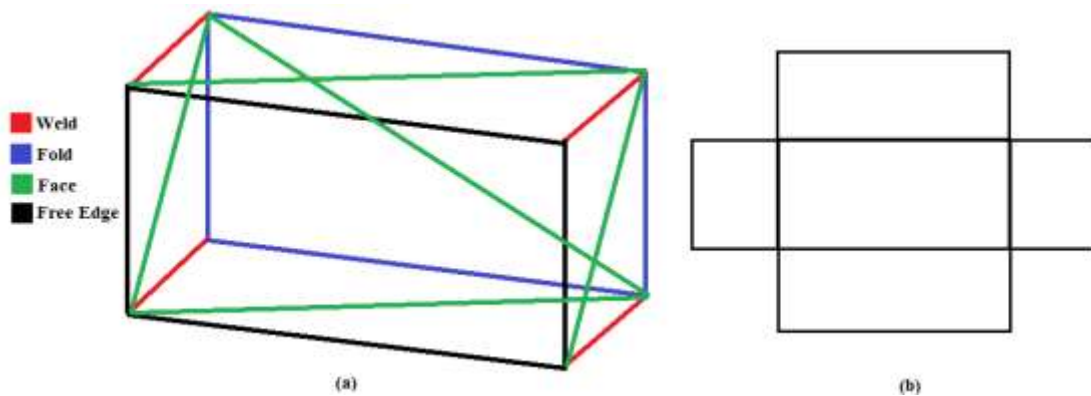
Figure 4.3 Elements classification to represent flat patterns. (a) Elements categorized according to lines types. (b) The flat pattern resulted of that categorization.

The stiffness matrix for each of the lines is multiplied by a parameter to indicate the actual stress-based ranking of the element under applied loads. The fold lines are weakened by a factor of 0.4 (Schenk et al. 2011), while weld lines are strengthened by a factor of 0.2, the face line is not modified; hence it takes the actual stiffness matrix of an element. The steps to determine the optimized flat pattern are illustrated in Figure 4.4.

The first step is to define the geometry in terms of nodes coordinates and elements, which leads to outline the connectivity of the structure. Afterwards the set of

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applied loads on nodes are defined in terms of magnitude and direction, while the boundary conditions step sets the degrees of freedom for each of the nodes. Then, the structural analysis is conducted without any modifications to the elements types, this way the lines with the potential high axial stress values are determined. The next stage includes assigning weld or fold lines for all those elements based on highest stresses found, the minimum number of seam lines equation, previously defined in chapter 2, is used to determine minimum number of weld lines required for each of the 3-D geometries. In the case of open box structure, the minimum number of weld lines is equal to four.

The final step of the analysis involves performing the structural analysis step again after modifying the stiffness factor for each of the assigned lines; this will also generate the flat pattern design, which is optimized in terms of stressed-based behavior. While the values for the high stress elements are reduced because of assigning welding lines to the majority of those elements.
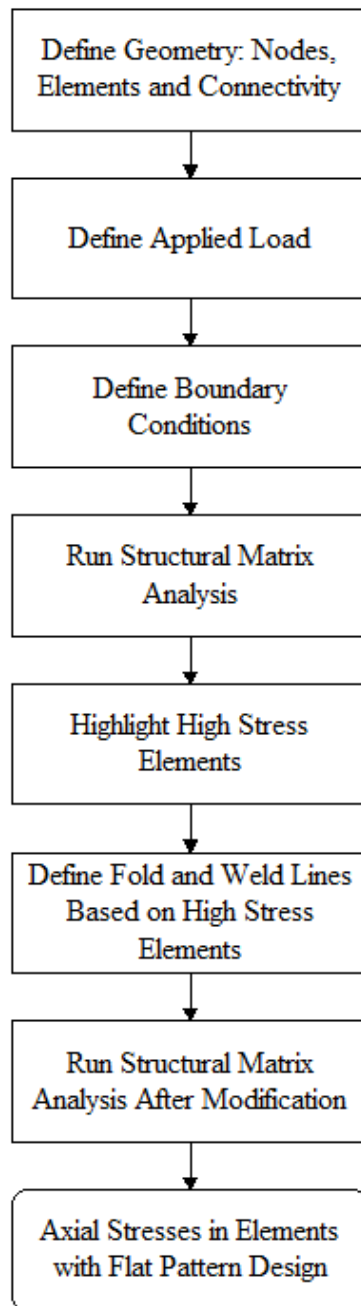
Figure 4.4 Steps followed in stress-based ranking of flat patterns.

4.6 Summary

This chapter handled the development of a methodology to conduct stress-based ranking of 3-D geometry under applied load schemes; the study utilizes the well-known structural analysis science that is used as the base for finite element analysis. The 3-D geometry of the folded sheet metal is modeled as a set of nodes and elemental trusses, with a polygonal approximation for all faces of the geometry.

The study counts for the flat pattern design by classifying the type of elements into three major kinds; those are weld, fold, and face lines, where each has a modification parameter considered during stiffness matrix generation to accommodate for the stress-based ranking.

The outcome of the analysis is the axial stress generated in each of the elements due to applied loads; this can lead to the optimized flat pattern design by assigning the high stresses elements as weld lines, whereas avoid assigning a fold line for those elements as a result of the material discontinuities, which weakens the material at fold line. In addition, the results of the optimum weld and fold lines location generates the optimum flat pattern in terms of its stress-based performance under the studied static loading.This approach had a great potential to assess the flat pattern profiles early in the design phase based on their stress-based behavior under predefined static loading scheme; this tool can provide sufficient initial evaluation for folded sheet metal products in terms of its stressed-based performance without the need for building a simulation models to investigate each flat pattern. Table 4.1 lists the major advantages of followed approach over traditional modeling option.

Table 4.1 Major advantages of stress-based ranking over simulation modeling.

Stress-Based Ranking	Simulation Using a Software
Mathematical Approach	Finite Element Approach
Consumes minimal time in modeling	Takes long time in modeling
Requires minimal modifications in modeling to accommodate flat patterns designs	Requires repeating the modeling for each flat pattern design separately

CHAPTER FIVE

OPTIMIZING FLAT PATTERN DESIGN FOR COMPOSITES MATERIALS

5.1   Introduction

In contrary to traditional materials, the properties of fiber- reinforced composites can be tailored to satisfy certain design requirements by manipulating the orientation of fiber content. They provide outstanding mechanical properties as lightweight, high directional strength, and corrosion resistance.

Among the several approaches to manufacture a fiber- reinforced composite part is the lay-up method, which is considered to be the most common. A single lamina is profiled on the pre-impregnated unidirectional composites sheets then cut-off. Afterwards the laminates are stacked in top of each other against a mold to compose the thin walled laminate. Conventional methods for designing composite structures include the use of Hooke's law for two-dimensional unidirectional composites and the application of elasticity theory to determine the final mechanical performance of specific lamina under certain loading conditions.

An important aspect to be investigated is the effect of selected flat pattern design on the final composite part, taking into consideration the fiber orientation and volume. This chapter deals with selecting the best flat pattern for a composite part design, which retains the best mechanical properties represented by fiber fraction and orientation, in addition to the best performance during joining operation.

The composite material application is addressed in the dissertation, since the application of Origami-based folded objects for different materials has a great potential especially with the merits that composites have in engineering applications. This chapter highlights the future expansion for Origami-based folding for other materials than metallic sheets and clarifies other dimensions for the study of flat pattern design in anisotropic material. In this work the effect of anisotropic material on the final flat pattern design is investigated in terms of parameters relating to the structure of composites, this leads to developing a procedure to relate the effect of material's properties on the optimum flat pattern design. Hence, the chapter adds a new prospective other than developing optimization metrics based on process or cost needs, rather the optimization metrics are based on materials' anatomy and parameters such as the fiber orientation, the peel shear and the direction of adhesively bonded joints relative to the fiber orientation.

5.2   Related Work

Published literature reported the several approaches to design fiber-reinforced composite materials, mainly using elasticity theory. Hull (1987) presented a comprehensive step by step approach for the design of composite laminate with extensive explanations of elasticity theory and the corresponding derived equations.

Composites materials are used in several applications as of aerospace and automotive components, Mangino et al. (2007) studied ten key aspects relating to composite usage in automotive industry, those are: repair, design, crashworthiness, manufacturing light weighting, joining, recycling, modeling, fire safety, and new material

concepts. Their work also addresses the challenges for wider use of composite materials in automotive industry.

Adhesive bonding is a feasible technique for joining composite materials though a designer should consider the joining process of a composite part during the early phase of design, since the low inter-laminar shear and tensile strength limit the joint efficiency and hence attention should be paid to the effect of fiber orientation on the final strength of the adhesive bond.

Parker (1994) investigated test methods for adhesive-bonded metal adherents to fiber-reinforced composites, the work considered the most critical factor in adhering fiber reinforced epoxy resin, which is the initial bond strength. On the other hand, Banea et al. (2009) examined the reported literature on adhesive bonding for fiber-reinforced plastic (FRP), the work also discussed the analytical and numerical methods of stress analysis required before failure prediction.

The problem of designing a flat pattern for lay-up composites was tackled by Lin (1993), the work addressed establishing screening rules for laminate to finally produce the best flat pattern design. With the aid of finite element analysis, the work defined the stress critical points and eliminated the flat pattern that provided higher stress concentration through defining butt joint locations. In addition, they developed geometrical factors to optimize the flat patterns in terms of total seam line length and the area of convex hull of a lamina. However, the work did not consider fiber orientation or volume in the flat pattern design.

5.3   Design of Composite Flat Pattern

5.3.1   Fiber Orientation

A lamina of fiber-reinforced composite is considered anisotropic, due to the directional strength relative to the fiber orientation. The difference between fiber orientation and loading direction controls the loading capability of a composite. It is widely accepted that loading in the same direction of fibers provides a lamina with higher strength values than exerting a load in the transverse direction.

In this analysis, the elasticity theory is used to determine the best fiber orientation for a lamina created from a flat pattern. As a first step, the analysis aims at defining the fiber orientation that results with the highest modulus of elasticity of a lamina. The followed approach defines the materials' mechanical properties for the fiber and matrix, in addition to the fiber volume fraction, which enables determining the values of ultimate strength that a composite material can sustain. The notations used through this analysis is confirming to the one used by Kaw's in (Kaw 2006). The X-Y directions are referring to the global coordinates of a composite, while 1-2 directions are referring to the local coordination of a lamina as indicated by Figure 5.1.
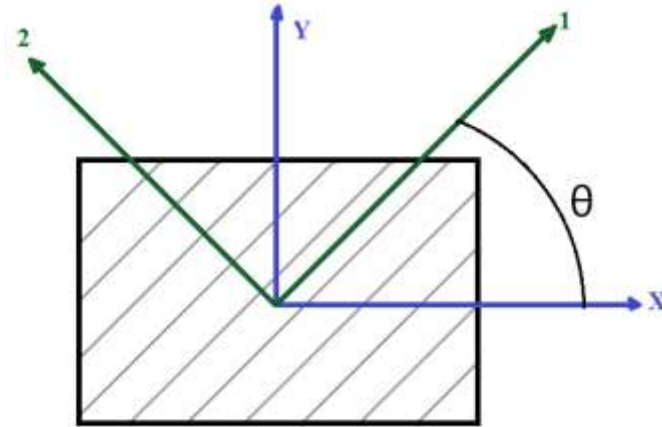
Figure 5.1 Local and global coordinates used in composite material analysis.

The value of ultimate longitudinal tensile strength $(\sigma_1^T)_{ult}$ is given in Equation (5.1), while ultimate strain of fiber$(\varepsilon_f)_{ult}$ and matrix$(\varepsilon_m)_{ult}$ are given in Equation (5.2) and (5.3), respectively.

$$(\sigma_1^T)_{ult} = (\sigma_f)_{ult}\ V_f + (\varepsilon_f)_{ult}\ E_m\ (1\text{-}\ V_f) \tag{5.1}$$

$$(\varepsilon_f)_{ult} = \frac{(\sigma_f)_{ult}}{E_f} \tag{5.2}$$

$$(\varepsilon_m)_{ult} = \frac{(\sigma_m)_{ult}}{E_m} \tag{5.3}$$

Where, E_m and E_f are the Young's modulus of matrix material and fiber material, respectively. V_f is the fiber volume fraction. $(\sigma_f)_{ult}$ is the ultimate strength of fiber. $(\sigma_m)_{ult}$ is the ultimate strength of matrix.

The ultimate longitudinal compressive strength $(\sigma_1^C)_{ult}$ is given in Equation (5.4), while the ultimate shear strength $(\tau_{12})_{ult}$ is given in Equation (5.6).

$$(\sigma_1^C)_{ult} = \frac{(\varepsilon_2^T)_{ult}\ E_1}{v_{12}} \tag{5.4}$$

$$\varepsilon_2^T = (\varepsilon_m^T)_{ult} \ (1 - V_f^{1/3}) \tag{5.5}$$

$$(\tau_{12})_{ult} = (\tau_f)_{ult} \ V_f + (\tau_m)_{ult} \ V_m \tag{5.6}$$

Where $(\tau_f)_{ult}$ and $(\tau_m)_{ult}$ denote the ultimate shear strength of fiber and matrix materials, respectively. The final ultimate strength components are the transverse tensile strength in case of tension$(\sigma_2^T)_{ult}$, and compression $(\sigma_2^C)_{ult}$, which are given in Equations (5.7) and (5.8).

$$(\sigma_2^T)_{ult} = E_2 \ (\varepsilon_2^T)_{ult} \tag{5.7}$$

$$(\sigma_2^C)_{ult} = E_2 \ (\varepsilon_2^C)_{ult} \tag{5.8}$$

The values of ultimate strength are compared to the resulted applied stress on the lamina to make sure that the lamina with certain V_f and determined fiber orientation shall sustain the applied stresses.

The developed approach here investigates the best fiber orientation that will result with highest strength of a lamina; this can be done by applying the elasticity theory (Hull 1987). The main challenge is to convert the stresses and strain values from the global to the local coordinates based on the values of fiber orientation, denote by angle θ.

$$\begin{bmatrix} \sigma1 \\ \sigma2 \\ \tau12 \end{bmatrix} = \begin{bmatrix} Q11 & Q12 & 0 \\ Q12 & Q22 & 0 \\ 0 & 0 & Q66 \end{bmatrix} \begin{bmatrix} \varepsilon1 \\ \varepsilon2 \\ \gamma12 \end{bmatrix} \tag{5.9}$$

$$\begin{bmatrix} \sigma_x \\ \sigma_y \\ \tau_{xy} \end{bmatrix} = \begin{bmatrix} \bar{Q}_{11} & \bar{Q}_{12} & \bar{Q}_{16} \\ \bar{Q}_{12} & \bar{Q}_{22} & \bar{Q}_{26} \\ \bar{Q}_{16} & \bar{Q}_{26} & \bar{Q}_{66} \end{bmatrix} \begin{bmatrix} \varepsilon_x \\ \varepsilon_y \\ \gamma_{xy} \end{bmatrix} \tag{5.10}$$

The formula in Equation (5.9) relates the local stress to the local strain of a lamina, while *[Q]* matrix is the reduced stiffness matrix. On the other hand, Equation

(5.10) relates the global stress values with global strain, while $[\overline{Q}]$ matrix is the transformed reduced stiffness matrix. Equation (5.11)-(5.15) are used to determine the elements in [Q] and $[\overline{Q}]$.

$$Q_{11} = \frac{E_1}{1 - \nu_{21}\nu_{12}} \tag{5.11}$$

$$Q_{12} = \frac{\nu_{12}E_2}{1 - \nu_{21}\nu_{12}} \tag{5.12}$$

$$Q_{22} = \frac{E_2}{1 - \nu_{21}\nu_{12}} \tag{5.13}$$

$$Q_{66} = G_{12} \tag{5.14}$$

$$\left.\begin{aligned}
\overline{Q}_{11} &= Q_{11}c^4 + Q_{22}s^4 + 2(Q_{11} + 2Q_{66})s^2c^2 \\
\overline{Q}_{12} &= (Q_{11} + Q_{22} - 4Q_{66})s^2c^2 + Q_{12}(c^4 + s^2) \\
\overline{Q}_{22} &= Q_{11}s^4 + Q_{22}c^4 + 2(Q_{12} + 2Q_{66})s^2c^2 \\
\overline{Q}_{16} &= (Q_{11} - Q_{12} - 2Q_{66})c^3s - (Q_{22} - Q_{12} - 2Q_{66})s^3c \\
\overline{Q}_{26} &= (Q_{11} - Q_{12} - 2Q_{66})c\ s^3 - (Q_{22} - Q_{12} - 2Q_{66})c^3s \\
\overline{Q}_{66} &= (Q_{11} + Q_{22} - 2Q_{12} - 2Q_{66})s^2c^2 + Q_{66}(s^4 + c^4)
\end{aligned}\right\} \tag{5.15}$$

$$\begin{vmatrix} \sigma_1 \\ \sigma_2 \\ \tau_{12} \end{vmatrix} = |T| \begin{vmatrix} \sigma_x \\ \sigma_y \\ \tau_{xy} \end{vmatrix} \tag{5.16}$$

$$\begin{bmatrix} \varepsilon_1 \\ \varepsilon_2 \\ \gamma_{12}/2 \end{bmatrix} = [T] \begin{bmatrix} \varepsilon_x \\ \varepsilon_y \\ \gamma_{xy}/2 \end{bmatrix} \tag{5.17}$$

$$[T] = \begin{bmatrix} c^2 & s^2 & 2sc \\ s^2 & c^2 & -2sc \\ -sc & sc & c^2 - s^2 \end{bmatrix}$$

(5.18)

The analysis of best fiber orientation demands the transformation from global to local stress; this can be conducted using Equation (5.16) – (5.18). Where, $c = \cos(\theta)$ and $s = \sin(\theta)$. The procedure calculates the Young's modulus of the composite at angles from 0-90 degrees with 10 degrees pitch and taking into consideration the load capabilities of a composite. Figure 5.2 illustrates the steps used to generate the Young's modulus for each specific fiber orientation.
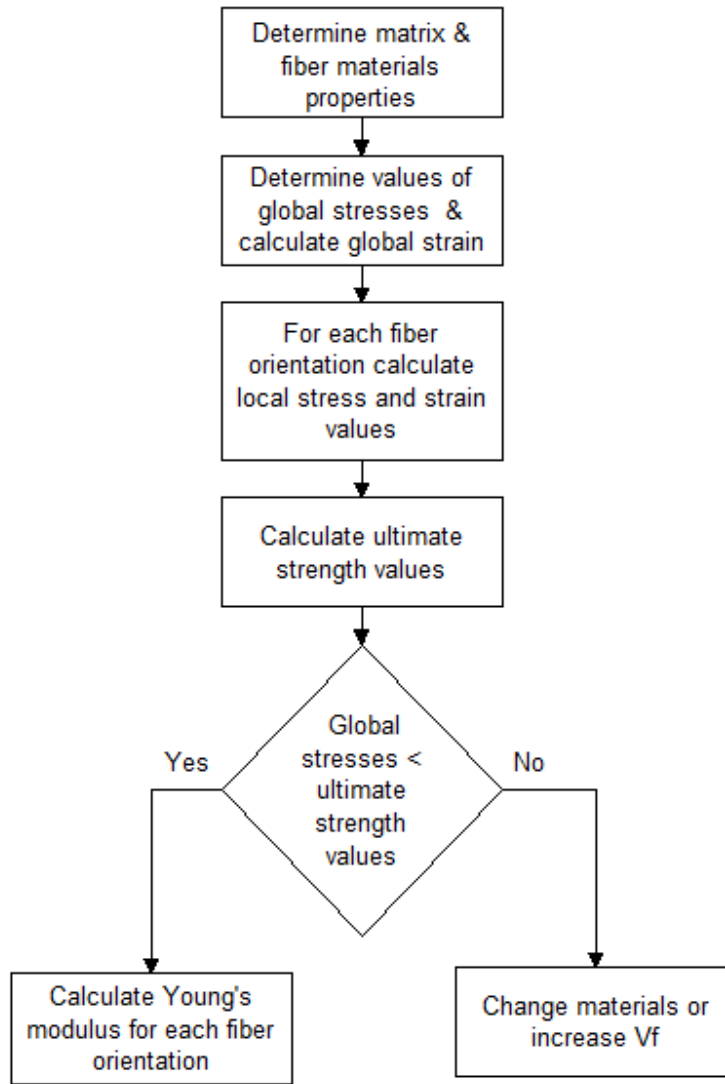
Figure 5.2 Steps followed to determine Young's modulus based on fiber orientation.

5.3.2 Total Length of Seam Lines

Up to this point in the analysis the shape of the lamina is not considered, since the fiber orientation is not dependent on the shape of the lamina. The second phase of the analysis for composite materials takes into consideration the effect of flat pattern design on the properties of the composite part. Each flat pattern of a 3-D part has different seam

lines arrangement, which can lead to different total length that needs to be joined. In case of a composite, the traditional joining process is adhesive bonding. The total length of the adhesively bonded joints affects the final strength of a composite part by adding critical stresses zones under peel shear. Hence, the part with minimum total joined length is anticipated to perform better under loading.

To investigate the best flat pattern for composites, the minimum spanning tree approach is utilized to search for the flat pattern with the minimum length of joined edges. This approach was used previously in this dissertation to determine the best flat pattern in terms of the welding cost. However, in the composite analysis the assigned values for each seam line edge in the weight-edge matrix represent the total geometrical length of that edge. Hence the MST algorithm generates the flat pattern that scores the minimum total joined length for a composite part.

5.3.3 Load Location

The third aspect used to investigate the flat patterns design depends on determining the adhesive bond strength based on load direction. The combination of fiber orientation and load direction, at the surface ply, affects the strength of a bond. Preferably, the fiber orientation of the surface ply should be designed parallel to load direction, i.e. peel shear. Figure 5.3 explains the effect of surface fiber orientation on the fracture load of a CFRP composite joined with adhesive.

In the case of flat pattern design, the fiber orientation and direction of load influence the selected flat pattern for a part to be made out of composite material. After defining the anticipated load direction and the fiber orientation of a lamina, the seam line

edges should be investigated for each flat pattern to select the one that complies with higher fracture load that means the flat pattern design that provide best combination of fiber orientation and load direction.
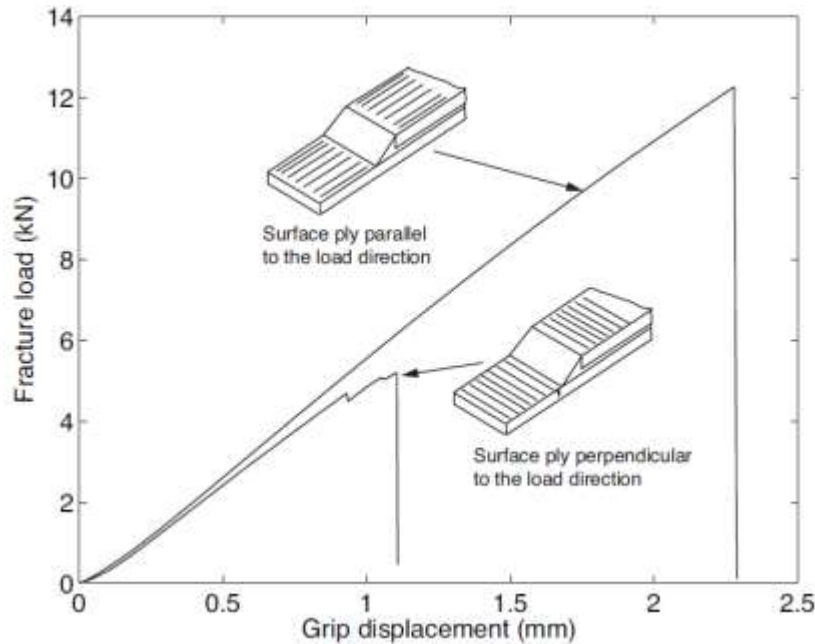
Figure 5.3 Effect of surface ply orientation on joint strength for CFRP and Epibond 1590 A/B adhesive. (Kelly 2004)

5.4   Non-manifold Structure Case

The non-manifold structure shown in Figure 5.4 is used to demonstrate the aforementioned procedure for flat pattern design in composite application. A lamina is produced from glass-fiber polyester resin with 30% fiber volume fraction; we need to consider the values of elastic constants of unidirectional lamina listed in Table 5. The principle global stresses applied on the lamina is assumed to equal 100 MPa for σ_x , 40 MPa for σ_y and 20 MPa for τ_{xy}. Figure 5.5 illustrates the Young's modulus values for

lamina with respect to each fiber orientation, where the highest value is corresponding to fiber orientation with 60 degrees.

The possible flat patterns for the part in Figure 5.4 are shown below in Figure 5.6. To determine the flat pattern with the minimum joined length the MST algorithm is applied. The assigned values in the edge-weight matrix correspond to the total length of the edge, for example edge connecting faces 1 and 2 is less preferable to be joined by adhesive bonding two times less than edge connecting faces 1 and 5 , this can be explained that edge 1-5 is longer in length than 1-2.
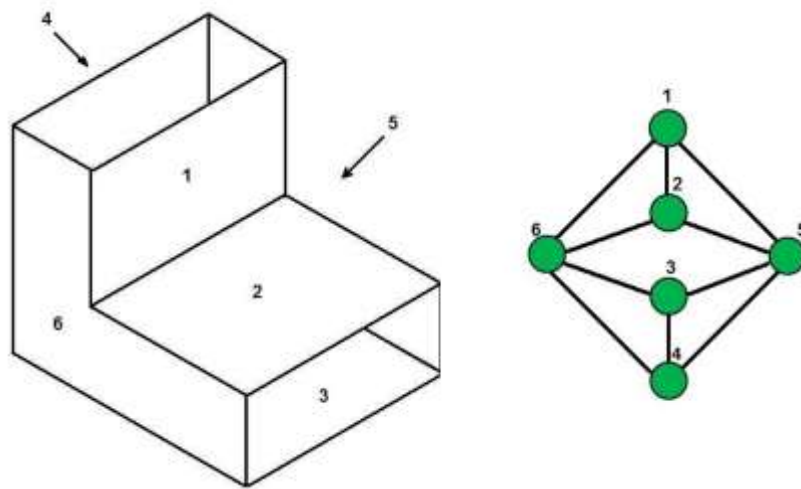
Figure 5.4 Non-manifold structure and its FAG.

Table 5.1 Values of elasticity constants for glass-fiber polyester resin with $V_f = 30\%$

Elasticity Constant	Value
V_f	30%
E_m	3.5 GPa
E_f	76 GPa
E_1	40 GPa
E_2	12 GPa
G_{12}	4 GPa
ν_{12}	0.26
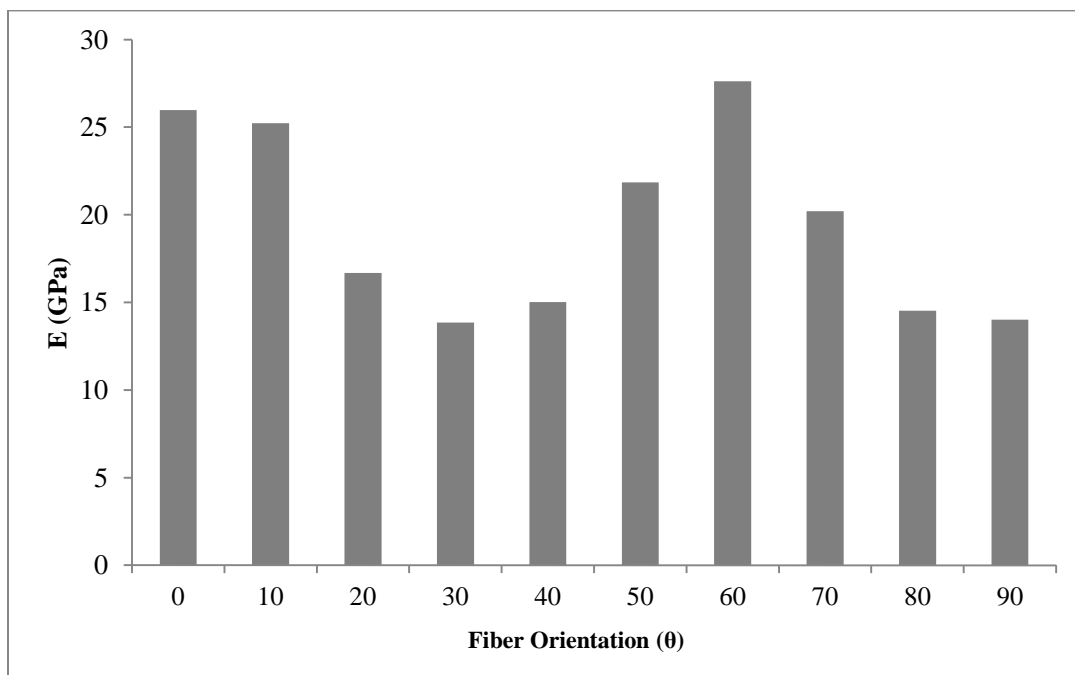
Figure 5.5 Young's modulus values with respect of fiber orientation of a lamina for glass-fiber polyester resin with 30% fiber volume fraction.
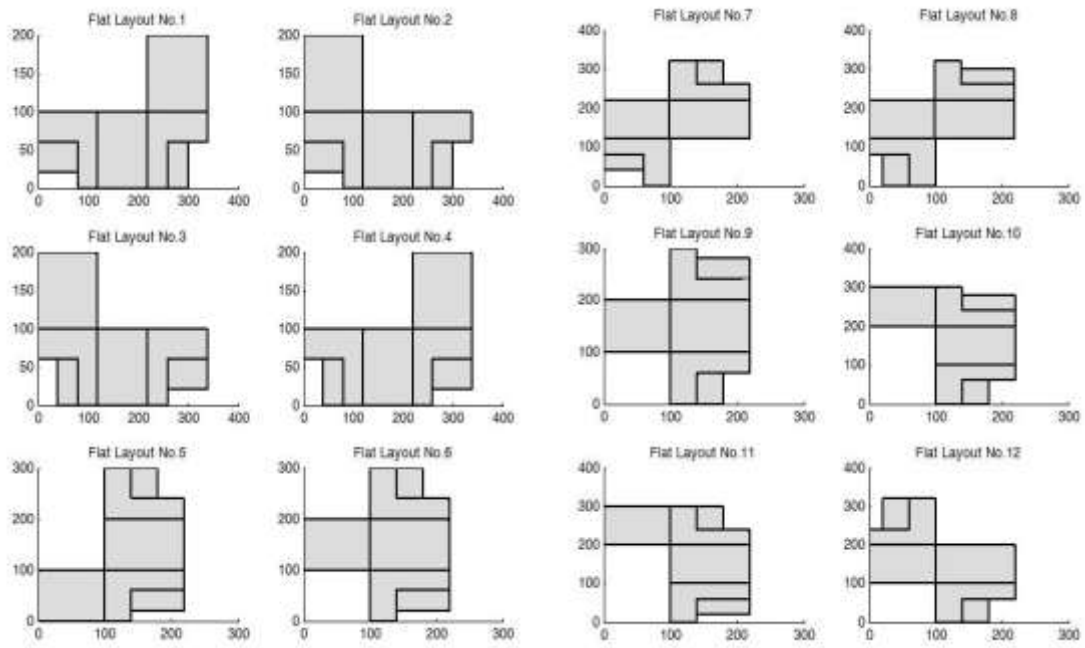
Figure 5.6 Possible flat patterns for non-manifold shape.

$$
\text{Edge-Weight Matrix} =
\begin{bmatrix}
1 & 2 & 20 \\
1 & 5 & 40 \\
1 & 6 & 40 \\
2 & 5 & 30 \\
2 & 6 & 30 \\
3 & 4 & 20 \\
3 & 5 & 10 \\
3 & 6 & 10 \\
4 & 5 & 20 \\
4 & 6 & 20
\end{bmatrix}
$$

The MST that corresponds to the minimum total joined length is shown in Figure 5.7(a), however this spanning tree produced an overlapping flat pattern due to the coinciding of face 1 and 5, which both are connected to face 2 in the MST. Searching for the next MST, Figure 5.7(b), replaces the connection 1-2 with 1-6 and it produces a valid flat pattern. The MST refers to flat pattern number 6 in Figure 5.6.

(a)   (b)
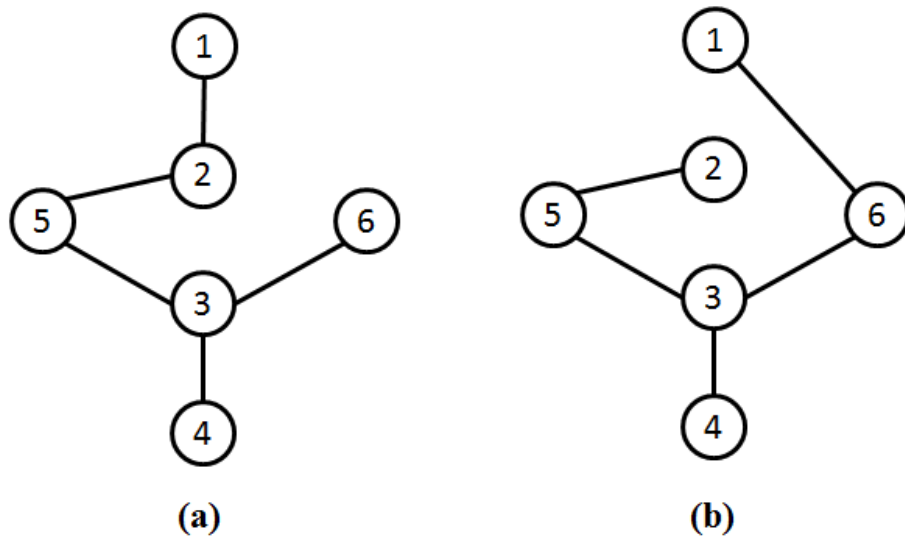
Figure 5.7 (a) MST with overlapping flat pattern. (b) Second MST with valid flat pattern

The third step of the analysis encounters determining the feasibility of MST flat pattern in terms of the load direction exerted on the adhesive bond in terms of peel shear. Figure 5.8 illustrates the seam lines edges assigned as adhesively bonded joints. Assigning the fiber orientation to 60 degrees as indicated previously in the analysis will result in weaker joints in terms of peel shear, according to Figure 5.5 , the difference between Young's modulus for $0°$ and $60°$ is not significant, hence we can replace the assigned fiber orientation with $0°$ instead of $60°$.

The fiber orientation on the load direction affecting the strength of adhesively joined edges negatively in two out of five joined edges, Figure 5.8, where joints 4-6, 1-5, and 5-4 are having the surface ply parallel to the load direction, while in case of the joint 1-2 the surface ply orientation is perpendicular to the load direction, which makes the joint weaker in terms of peel sear and the fracture load is considerably decreased. The joint 2-6 is having a combination of parallel and perpendicular surface ply which is considered weaker than joints 4-6, 1-5, and 4-5. Whereas, 2-6 is stronger than joint 1-2, alternative ways to increase joint strength can be through increasing the overlap length and changing the end effects of joints (Kelly 2004).
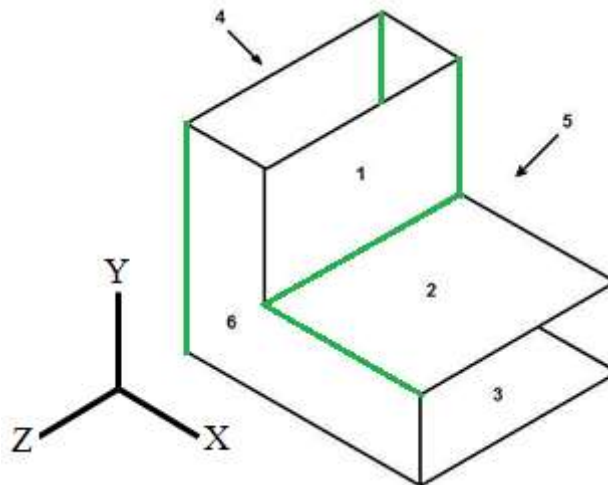
Figure 5.8 Seam lines for L-shape flat pattern.

5.5   Summary

The process of designing a 3-D folded component of composite material has been studied in this chapter, the composite material analysis focused on the effect of materials anisotropy on the optimized profile of flat pattern. The study structured analysis steps

considers three major parameters, those are fiber orientation, total length of seam lines, and load location with respect adhesive joints.

The optimum fiber orientation is determined by applying the elasticity theory for composite materials, where the fiber orientations from 0-90 degrees are investigated to locate the angle that produces the highest strength of the composite material. Up to this point, the flat pattern profile is not affected with the fiber orientation. Nonetheless, the fiber direction affects the adhesive joint strength. The second parameter is the total length of seam lines (i.e. weld lines), since the total joined length of a composite material affects the final strength of the composite component. Finally, the load direction of peel shear at the adhesively bonded joints is considered, the effect of fiber orientation and peel shear are studied to avoid transverse direction that lowers the fracture load of a joint.

CHAPTER SIX

KNOWLEDGE-BASED SYSTEM FOR FOLDED SHEET METAL DESIGN

6.1   Introduction

The previous established analysis of this dissertation dealt with the folded sheet metal product wise. However, the fold forming process itself requires evaluation tools to determine its feasibility to fabricate certain part design or serve as main manufacturing process within a production line. This chapter handles the formation of a Knowledge-Based System (KBS) to assess the fold forming process for certain production and process requirements in addition to benchmarking to other traditional manufacturing processes.

The variability and dynamics in the real world require the designers to change or modify their designs to accommodate changing customer needs and industrial new trends. However, along the product or process life the human knowledge and expertise experiences variability and changes as well. Intelligent systems such as knowledge-based systems are utilized to preserve and store the needed proficiency of a certain field, thus it is available along all design phases. KBS is engaged in engineering applications to offer intelligent decisions for vast area of fields, as in cases of material selection (Sapuan 2001) (Edwards 2005), product and tooling cost modeling (Tang et al. 2004),(Shehab et al. 2002) and product and process design (Chapman et al. 1999) , (Tang et al. 2001).

The integration of various analysis tools within KBS increases the efficiency and domain spread for the captured knowledge. This work investigates the problem of designing a production line for automotive structures, specifically Body-in White (BiW) panels, while incorporating the requirements validation tools and decision making approaches, namely Quality Function Deployment (QFD) and Analytical Hierarchy Process (AHP).

QFD possesses outstanding usefulness in achieving customer requirements in a product or service; it is a comprehensive tool to interpret the customer requests into the appropriate technical requirements for each phase of product or process development (Sullivan 1986). Applying QFD can maintain customer satisfaction as the core focus, reduce design and development time and enhance communication among all levels of an organization (Myint 2003). However, the method followed to determine the weights of customer needs are not based on prioritizing besides the ranks are subjective, which led to the use of AHP as a prioritizing tool to indicate the importance of customer needs (Tu et al. 2011). Employing Analytical Hierarchy Process (AHP) in combination with QFD improves the analysis results through reflecting prioritization of needs and attributes in the evaluation criterion.

Coupling the KBS with QFD and AHP, in general, is anticipated to achieve the following merits:

- Reduce the development and analysis time needed to launch a new design or existing design modifications; since the system enables analysis process automation.

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- Capture and preserve the experience and knowledge gained to utilize QFD and AHP tools for a certain application.

- Enable the designer to perform what-if analysis by changing or modifying design requirements and attributes with least effort and time.

- Offer consistency in approaching a design problem; the system can track back the root cause of design errors and justify each assumption made.

- Provide a user-friendly environment, which enables broader usage for the system in the facility.

6.2 Literature Review

Employing artificial intelligence tools as KBS along with QFD and/or AHP were discussed in published literature for various applications. (Rao et al. 1999) presented a model and survey for the application of expert systems in new product development, among the applications discussed is the utilization of KBS with QFD for new product design for areas as the interpretation of customer requirements into product specifications and quality emphasizing by converting the design into quality manufacturing, However, the study focused only on new product development coupled with artificial intelligence. On the contrary, (Chan et al. 2002) offered another survey focused only on QFD applications by searching 650 publications dealing with QFD, the work classified the major QFD areas to be in product development and design, quality management, customer needs analysis, process planning, decision making, costing and timing problems. The cross matching between previously listed areas for KBS and QFD or

amalgamation of both shows common interests between the applications with increasing merits for combined systems.

Myint (2003) established a system for discrete assembly design by employing Intelligent Quality Function Deployment (IQFD) that is a combination of traditional QFD and neural network. The work coped with the uncertainty in the available human experts in product development cycle. In addition, AHP identified priorities of customer needs and the experts systems mainly aimed at dealing with variable weights. However, the presented neural network gave no consideration for the variability in requirements and attributes during the development cycle.

Other programing techniques can be utilized to deal with variability in QFD as in Raharjo et al. (2006) work; he used linear programming model and quality-loss function to rank the quality characteristics of product with respect to meeting customer voice. In addition the study dealt with the variability in future customer needs by forecasting techniques as well as customer importance rating. Nevertheless, the system assumed independent effects of quality characteristics on variability and merely a linear relationship between the optimization function and quality characteristics.

Process design and selection can also be tackled using a hybrid system of KBS and QFD tools, Chakraborty et al. (2007) established a QFD for the selection of optimal non-traditional machining process using an expert system. The work employed House of Quality (HoQ) matrix comparison between the product and processes characteristics, and stored the information of scores values with the various attributes of material requirements; hence it added high simplicity and flexibility. However, the characteristics

are fixed within the analysis, with the ability to update the manufacturing processes options in the database.

In terms of automotive industry, Jariri et al. (2008) discussed an automotive platform design using a mathematical programing cost model that employed QFD data to present an initial design. Yet, the study did not tackle the customer needs; instead it evaluated various alternatives for system components to satisfy cost constraints. Additionally, Mayyas et al. (2011) handled the material selection problem for vehicular structure by employing QFD and AHP techniques for conceptual design of BiW. The study focused on rating the material nominees in the order of their performance towards achieving the functional goal of an automotive panel, as dent resistance and bending stiffness. The study used both analytical tools to generate candidates for BiW panels. However, the system did not include any form of an expert system, in addition to no variability or dynamics were of importance to the conducted analysis.

Uncertainty and variability in customer needs were investigated by Raharjo et al. (2011); where he established a system to deal with the variations in customer needs in terms of their weights in QFD. The work used forecasting as a modeling tool for a dynamic AHP in addition to changes in relative weights overtime.

6.3 Methodology

6.3.1 Intelligent Quality Function Deployment (IQFD)

The usage of QFD in this work aims at translating the manufacturing process attributes, which are extracted from customer needs, into automotive production line

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requirements. The skeleton of the translation phase is KBS oriented that enables continuous consultation with knowledge bases. Through this study, the incorporation of KBS with QFD is referred to as IQFD; it stores all established expertise and rules in knowledge bases and retrieves the data for new cases by employing Rule-Based Reasoning (RBR).

Hose of Quality Knowledge Bases

House of Quality (HoQ) is the structured relationship mapping between the process attributes and the production requirements. In a manufacturing HoQ for production line design, the WHATs represent the process attributes and HOWs represent the production attributes. The mapping in IQFD is a HoQ matrix that helps relate the rows and columns quantitatively based on scores provided by the designer. The generated outcomes of IQFD communicate the importance and comparative ranking of the specified process attributes, the outcome also ranks the production line requirements towards the accomplishment of process attributes. Figure 6.1 shows the structure and components of HoQ.
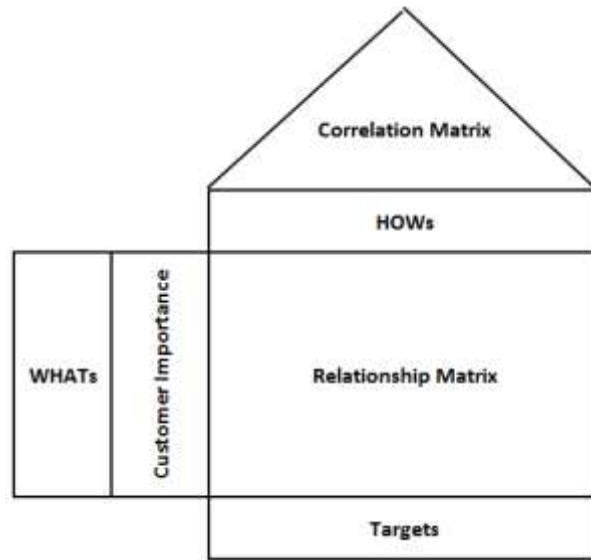
Figure 6.1 House of Quality structure and components.

This analysis uses a four-phase model (Hauser et al. 1988) that involves four sequenced HoQ stages shown in Figure 6.2. KBS can be implemented during the four-phase, which enhance analysis and capture experience along the development process. The four phase model takes customer needs as inputs and produces the production requirements along with their importance ranking. Initially, the examination is associated with translating pure customer needs in a vehicle into engineering characteristics, followed by parts deployment that transforms the engineering characteristics into parts features. Afterwards, the process-planning matrix converts parts features into key process attributes. Finally, the production-planning matrix turns the key process features into production requirements. The subsequent sections identify the components used to build the production-planning matrix to deign automotive production line through KBS.

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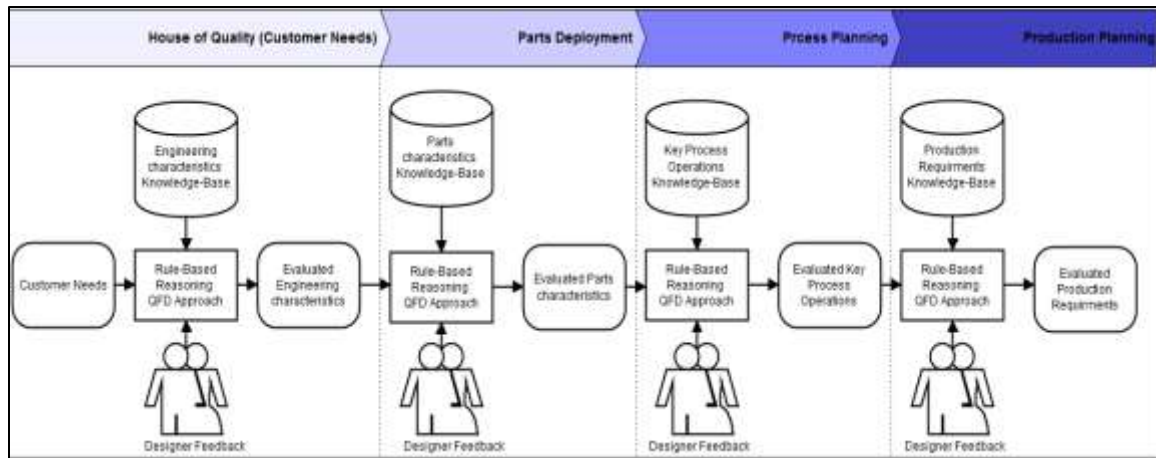
Figure 6.2 The four matrices model for HoQ implemented by KBS.

Process Attributes Knowledge Base (WHATs)

Key process attributes are the important objectives or the production targets that when achieved would result in cost and timesaving by the Original Equipment Manufacturers (OEM). They can also be classified as the shop floor requirements, which when optimized would enhance the overall efficiency of the production line. In this work eight major process features are investigated and feed into the knowledge base. Furthermore, IQFD component provides the user with ability to define new process attributes and add them to the knowledge base. The initial knowledge base lists the following process attributes as major parameters towards customer satisfaction, those are:

a) Reduction in lead time; referring to the minimization of time spent by raw material to be transformed from metal coils/sheets to completed BiW panels. This process

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attribute contributes to lower idle capital costs, lower operating costs and faster response to a change in the product mix or variety.

b) Fewer operations; which affect the number of operations required shaping the raw material into the final usable BiW panels form. Fewer operations lead to shorter lead time, less material handling requirements, better production planning efficiency, and lower utilization of machinery that add to the capacity of production line

c) Reduction in operational complexity; that is a qualitative measure of the effort undertaken by body shop personnel to ensure that the produced BiW panels are fabricated to the final outline and dimensions as required by designs blueprints. The evaluation procedure of operational complexity takes account of the usage of specialized forming fixtures, the number of vital shots necessary to form the intricate shapes, and the indispensable utilization of special die designs.

d) Standardization; denoted by the standard manufacturing operations to cover most of the BiW panels designs.

e) Ease of reconfiguration; where reconfiguration is referring to the compulsory changes in process layout and machinery to accommodate fluctuations in product variety. In automotive production line, different models of passenger vehicles require body panels of different dimensions, material, and shape. The changes in BiW panels oblige alterations in forming techniques. Therefore, the performance of automotive production line can score higher reconfiguration level through use of standardized parts and modularized body panel sub-assemblies.

f) Automation; which features the performance of production line in terms of its spontaneous sequence of operations, as automated material handling and loading/offloading of blanks. The production line automation improves efficiency, decrease time, reduce human fatigue and eliminate error due to human factors.

g) Scrap reduction; that is the increasing in material utilization percentage. Scrap can be reduced by optimized nesting configuration of panels and consolidation of smaller parts.

h) Decrease in rework; which refers to the wasted resources caused by defects in parts. BiW panels are evaluated based on dimensions, appearance and strains. Any nonconformance in these characteristics will lead the component to be recycled or scraped.

Customer Importance Knowledge Base

In the case of the fourth-matrix, its importance scores represent the effect of key process attributes in realizing customer satisfaction. The given range for importance scores is regularly from 1 to 10, where 1 being the least significant. The stored customer importance for each process attribute in the knowledge reservoirs of IQFD are based on designer's proficiencies and expertise. Table 6.1 lists the given importance scores for each specified process attribute.

Table 6.1 The list of initial process attributes and their importance score.

Importance (α)	Process Attributes ("WHATs")
9.0	Reduction in lead time
9.0	Fewer operations
3.0	Reduction in operational complexity

6.0	Standardization
6.0	Ease of reconfiguration
6.0	Automation
3.0	Scarp reduction
3.0	Decrease in rework

Production Requirements Knowledge Base (HOWs)

The production requirements in this work are defined as the engineering characteristics for the automotive production line that are determined by the product development team. For every process attribute (WHAT), there are designated technical attributes and a particular direction of improvement, i.e. if it has to be increased, decreased, or left to be the same. The knowledge base of IQFD initially defines ten production line requirements. It similarly provides the user with ability to define and store more requirements. The detailed automotive production line requirements fed into the knowledge base are listed as below:

1) Number of components: This requirement refers to the total number of components that form the final BiW structure. It includes major panels and sub assembles provided by the supplier. Reducing the part count will decrease cost, manufacturing lead-time, and material handling time.

2) Changeover time: That is the time consumed in changes for tooling and operation setup to accommodate alterations in BiW panels. It is affected by degree of standardization and ease of reconfiguration required by the process to fabricate the needed panel's design.

3) Uniformity in material selection: Different BiW panels require different materials to satisfy various requirements of surface finish, strength, and torsional strength.

For instance a door inner and outer would require different materials; therefore, specialized joining techniques would be essential. The reduction of material variety leads to lower cost and time during joining process similar to welding or adhesive bonding.

4) Variability in dimensions: For BiW panels, thicker exterior panels increase crash and dent resistance, while thinner interior panels help reduce weight. The best manufacturing process in terms of variable dimensions is the one that can handle different thicknesses with least cost, number of operations, and complexity.

5) Intricate shapes: That denotes the complex shape of BiW panels, which affects the number of operations needed to reach the desired profile. Parts complexity also increases the cost and handling requirements of BiW production line.

6) Usage of common platform: This can be referred to as the development of modular systems that facilitates interchangeability between vehicle models. Modularity increases standardization, reduces rework but increases the lead-time of fabricating modules.

7) Open architecture control: An open architecture control for the machinery facilitates reconfiguration procedure. In consequence, parameters like capacity, operations sequence, alignment, and power requirements can be modified using remote production control units. This modification enhances faster response to change in product mix.

8) Nesting optimization: The material utilization is directly affected by the arrangement of panels' patterns over stock i.e. nesting of patterns. Optimized nesting reduces scrap generation and reduces cost.

9) Consolidation of parts: This concept denotes merging or combining multiple functions in one component, which cuts cost, achieves weight savings, decreases production lead time, increases standardization reduce number of operations.

10) Intra-cell and inter-cell distance: The optimization of process sequence and production floor layout reduces the travelled distances. This helps achieve lower product lead-time and material handling cost associated with operations such as welding and painting of BiW panels.

Correlation Knowledge Base

The connections between each process attribute and each production requirement are stored in the correlation knowledge base. Through IQFD system, the correlation between process attributes *i and* production requirement *j* is denoted as $\beta_{ij.}$ The correlation is descriptive in nature with ability to translate user's preferences for evaluation range; the qualitative correlation describes the relation as being weak, moderate, or strong. This classification depends on the effect that a production requirement induces on a process attribute as the value of a production requirement changes. In addition to the correlation assessment, the correlation knowledge base categorizes whether each production requirement experiences an increase, decrease or no change status towards accomplishing the process attributes.

Rule –Based Reasoning (RBR) for IQFD

The previously discussed knowledge bases own significant information about process attributes and automotive production line requirements. Yet, the knowledge bases are incapable of producing sophisticated judgments or perform any analysis. This study employs RBR to execute logic tasks that examines the content of knowledge bases and generates analysis results in return. RBR can be seen as a reservoir of IF-THEN rules that shapes the relationship between all contents of knowledge bases.

The RBR conducts analyze based on five stages, within each stage the system retrieves knowledge and executes the rules associate with it. Figure 6.3 shows the outline for file sequence activated during study. The fourth step mandates that all process attributes that provided to IQFD system, either from user input or selected by user from knowledge base, to be evaluated first. Then the system evaluates the weighted correlation, denoted by *W*, for production requirements based on a ranking score that is determined by Equations (6.1) and (6.2)

$$W_{ij} = \alpha_i \, \beta_{ij} \qquad\qquad (6.1)$$

$$W_j = \frac{\sum_{i=1}^{n} W_{ij}}{\sum_{j=1}^{m} w_j} \qquad\qquad (6.2)$$

Where, W_{ij} is the weighted correlation for the processes attribute *i* and production requirement *j*. W_j is total weighted correlation for production requirement *j*. α_i is the customer importance score of process attribute *i*. β_{ij} is the correlation between process attribute *i* and production requirement *j*. *n* is the total number of process attributes. *m* is total number of production requirements.

The results of IQFD analysis are the values of total weighted correlation, *Wj*, for each production requirement. Hence, IQFD ranks the production requirements with respect to their effect in customer satisfaction, where the voice of customer is represented by the process attribute list and the customer importance scores.The role of rules stored in the KBS is to judge the content of the knowledge bases according to predefined logic; Figure 6.4 illustrated the triggered rules if the process attribute "scrap reduction" is declared by user to be in process attribute list for a case analysis, the matching step triggers all rules associated with scrap reduction and retrieve the pieces of information related to that process attribute, in addition the correlation stage allocate a value for each combination of process attributes and production requirements placed in the pools. To convert the correlation values from qualitative values to numerical form, the third step of evaluation triggers rules that link each assigned qualitative value to a quantitative one.
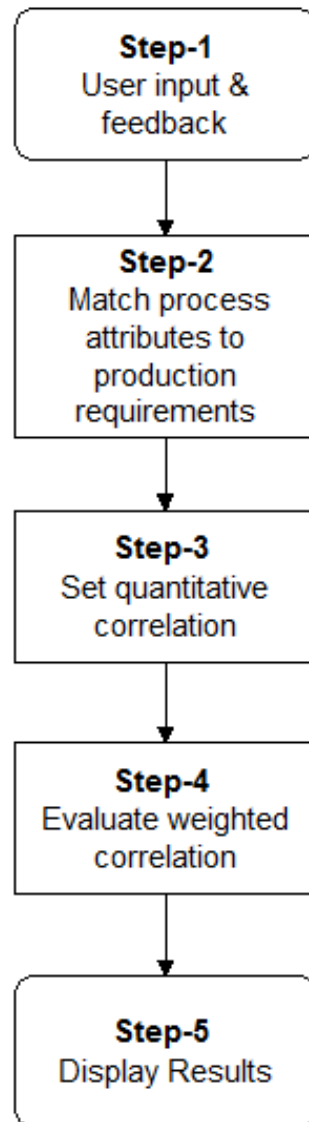
Figure 6.3 The system outline during RBR evaluation.

```
Step-1 User Input
List of process attributes: "Scrap Reduction", Importance is 3.0
Range of correlation [1-10]
Step-2 Matching
IF
"Scrap reduction" belongs to process attributes
THEN
List "nesting optimization" in the production requirement pool.
List "Consolidation of arts" in the production requirement pool.
List "Avoiding Intricate shapes" in the production requirement pool.
List "Number of components" in the production requirement pool.
End
Step-3 Identify Correlation
IF
"Scrap reduction AND "Nesting optimization"
THEN
Correlation is "Strong" AND 9
IF
"Scrap reduction" AND "Consolidation of parts"
THEN
 Correlation is "Moderate" AND 3
IF
"Scrap reduction" AND "Change over time"
THEN
No matching found AND correlation is "Weak" AND 1
END
```

Figure 6.4 Pseudo code for scrap reduction process attribute.

6.3.2 Intelligent Analytical Hierarchy Process (IAHP)

The second stage of the analysis deals with selecting a manufacturing process that best suits the production requirements. In this work, the built KBS employs AHP selection procedure to favorably decide on a fabrication process for the BiW panels. The incorporation of AHP analysis in KBS is referred to as IAHP through this work. The fusion of IQFD and IAHP in one system is illustrated in Figure 6.5. The outcomes of

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IQFD component are used as inputs by IAHP; as the results of IQFD component are set as the essential selection criteria to favorably select between the various available manufacturing processes. The IAHP retrieves the available production requirements with the assigned weights and conduct the AHP analysis for all available manufacturing processes in a knowledge base. The reasoning logic is built to accommodate AHP selection steps.

Among the various production requirements, the system shall select those of importance relative to the customer needs as translated from the IQFD system, in addition to their final weights. The lowest layer of the hierarchy contains all manufacturing processes alternatives under concern. Each fabrication approach is scaled against all other options in the local pair-wise ranking.

The IAHP approach conducts pairwise comparison to measure the relative significance and evaluate alternatives at the lowest level of the hierarchy, which enables the transformation of subjective judgments into objective measures. As a decision making tool, AHP distinguishing feature is the ability to perform on qualitative and quantitative levels (Chen et al. 2007). The qualitative level assists in formalizing an unstructured problem into a systematic hierarchy in the decomposition phase. Afterwards, the quantitative approach conducts prioritizing by numerical values and weights for the pair-wise comparison; it specifies the ranking on the pair-wise level and the final overall stage of hierarchy.

The amalgamation of AHP in a KBS, namely IAHP, increases the system efficiency and results consistency. Moreover, the system saves all previously conducted analysis to provide the designer with experience gained from earlier designs and cases. IAHP can accommodate fluctuations and variability in weights through the design phase as well. Figure 6.6 shows the two IAHP levels and their steps.
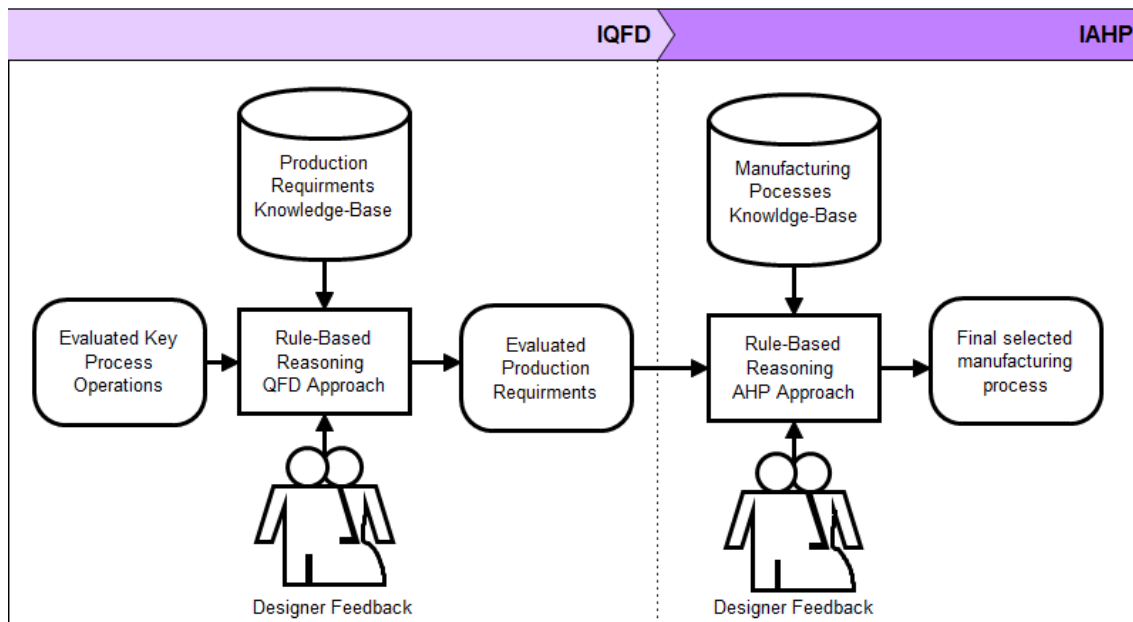
Figure 6.5 The integration between IQFD and IAHP in the analysis.
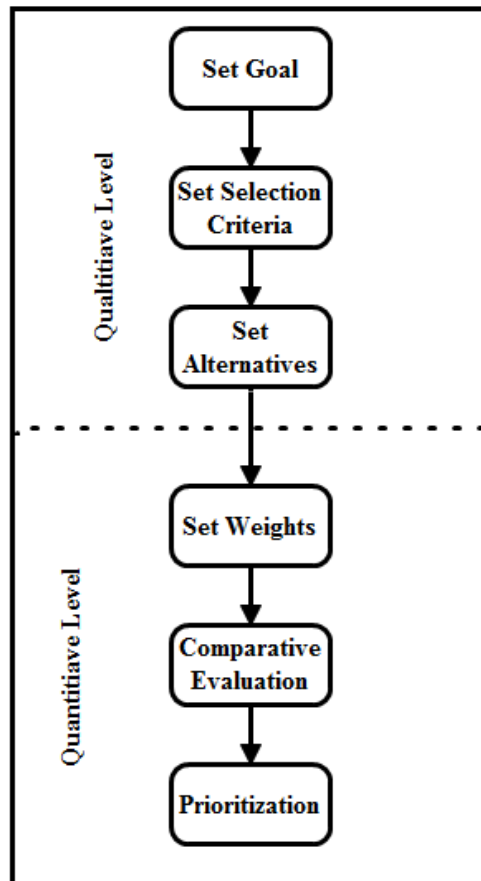
Figure 6.6   Stages and steps of IAHP.

Qualitative Level Knowledge Bases

The qualitative stage of IAHP formulates the decision problem into three categories: objective, selection criteria, and alternatives. Structuring of the selection problem assists in ordering the elements in systematic logical layers, which enables extraction of conclusions. Typically, the process of structuring involves the identification of the problem, the elements involved in the problem, requirements, criteria, and available alternatives. Afterwards, clustering of similar elements brings homogeneity by level (Saaty et al. 2009).

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Manufacturing Processes Knowledge Base

The major knowledge base for qualitative level is concerned with manufacturing processes; where all designers' expertise about BiW panels manufacturing approaches is stored. The system initially contains main five manufacturing process with the ability to modify, add, or exclude manufacturing processes based on designer choice. Those fabrication methods are listed below:

a) Sheet Metal Stamping (SMS)

b) Metal Casting (MC)

c) Sheet Metal Fold Forming (SMFF)

d) Sheet Hydroforming (SH)

e) Superplastic Forming (SF)

Comparative Evaluation of Alternatives (CEA) Knowledge Base

The comparative assessment in AHP is based on pair-wise evaluation for the available alternatives with respect to every evaluation parameter. In this work, the IAHP component runs the CEA step by rating the performance of every manufacturing process against other alternative processes in achieving the intended change in one production requirement parameter i.e. increasing or decreasing direction.

The CEA knowledge base contains all the characteristics and abilities of each manufacturing process with respect to production requirements. For example, SMS process is evaluated in terms of all production requirements initially stored in the IQFD component and so forth for the rest of manufacturing processes available in the

knowledge base. However, the evaluation is relative in nature and is represented in pair-wise comparison among each possible pair of manufacturing processes.

IAHP component uses both descriptive and numerical values to conduct the CEA, where the knowledge base contains a fundamental scale of 1-9 to estimate dominance during the evaluation since the comparison parameter is intangible; the scale is consistent with the transformation of subjective judgment to absolute values made by Saaty (2008). In addition to the predefined scale, the CEA knowledge base holds the experience of design engineers in locally rating manufacturing processes against each other. Figure 6.7 illustrates the definitions of the absolute numbers. As an example of CEA knowledge base content, if SMS process is compared to SH process in terms of cycle time reduction, then SMS scores very strong dominance with 7 times better than SH in achieving reduction in cycle time. Moreover, when SH is graded against SMS the absolute numerical value is set as 1/7.

Relative Importance (Numerical)		Relative Importance (Descriptive)
9		Exterme
8		Very Very Strong
7		Very Strong
6		Strong Plus
5		Strong
4		Moderate Plus
3		Moderate
2		Slight Equal
1		Equal
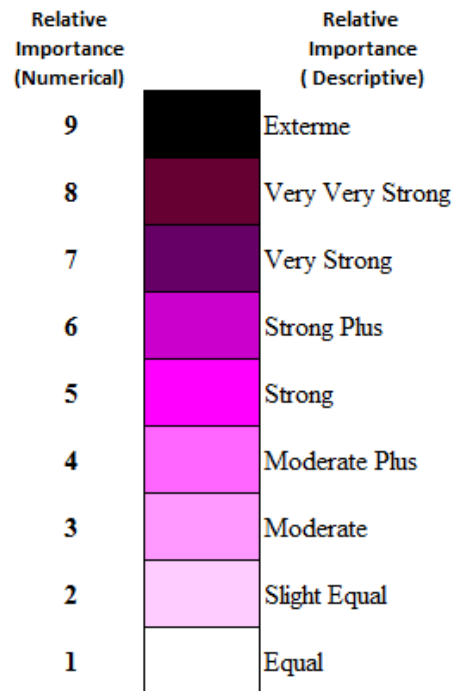
Figure 6.7 Importance score scale for CEA.

Table 6.2 lists the numerical values for CEA with respect to the initial production requirements that initially exist in IQFD knowledge bases. The matrix of evaluation is symmetric; hence one side of evaluation is sufficient to represent the assessment. In addition to the predefined assessment for the ten production requirements, the user can input evaluation values for new production requirements and store it in the CEA knowledge base for future analysis.

Comparative Evaluation for Criteria (CEC) Knowledge Base

CEC is the pair-wise assessment of the selected evaluation factors with respect to reaching the goal. In our case, it is the performance of each production requirement in

affecting the selection of a manufacturing process for BiW panels; those production requirements are identified by IQFD phase.

The developed system follows two possible routes to launch the comparative evaluation for production requirements. First track is based on extracting the information of the comparative evaluation from the IQFD outcomes, which are the targeted weights of production requirements, previously denoted by *Wj*. On the other hand, the second path is based on new evaluation values provided by the user to establish new assessment analysis. All new values are stored in the CEC knowledge base to be recalled for future cases; hence the system builds experience and functions as a knowledge management tool. Furthermore, the score scale shown in Figure 6.7 is followed to determine the new CEC values if user choose to take the second route.

Table 6.2 Summary of CEA for initial production requirements stored in the system.

P1- No. of Components ↓

	SMS	MC	SMFF	SH	SF
SMS	1	1/5	1/3	1/8	1/8
MC		1	4	2	2
SMFF			1	1/2	1/3
SH				1	1/2
SF					1

P2- Changeover Time ↓

	SMS	MC	SMFF	SH	SF
SMS	1	3	1/3	4	3
MC		1	1/5	1/3	1/4
SMFF			1	3	3
SH				1	1/2
SF					1

P3- Uniformity of Material ↑

	SMS	MC	SMFF	SH	SF
SMS	1	1/3	1/4	1/6	1/4
MC		1	1/2	1/5	1/2
SMFF			1	1/3	1/2
SH				1	2
SF					1

P4-Variability in Dimension ↓

	SMS	MC	SMFF	SH	SF
SMS	1	3	3	1/2	1/2
MC		1	1/3	1/3	1/3
SMFF			1	1/5	1/3
SH				1	1
SF					1

P5-Intricate Shapes ↓

	SMS	MC	SMFF	SH	SF
SMS	1	2	3	1/4	1/3
MC		1	3	1/3	1/4
SMFF			1	1/5	1/6
SH				1	2
SF					1

P6-Common Platform ↑

	SMS	MC	SMFF	SH	SF
SMS	1	1/4	1/2	1/6	1/5
MC		1	2	1/3	1/2
SMFF			1	1/5	1/3
SH				1	4
SF					1

P7- Open Architecture ↑

	SMS	MC	SMFF	SH	SF
SMS	1	1/2	1/6	1/3	1/3
MC		1	1/4	1/5	1/5
SMFF			1	2	2
SH				1	1
SF					1

P8-Nesting ↑

	SMS	MC	SMFF	SH	SF
SMS	1	6	1	3	3
MC		1	1/6	1/2	1/2
SMFF			1	3	3
SH				1	1
SF					1

P9-Consolidation of Parts ↑

	SMS	MC	SMFF	SH	SF
SMS	1	1/2	1/4	1/6	1/7
MC		1	4	2	1/3
SMFF			1	1/3	1/2
SH				1	2
SF					1

P10- Inter cell & Intra-cell Distances ↓

	SMS	MC	SMFF	SH	SF
SMS	1	2	1/4	1/2	1/2
MC		1	1/4	1/2	1/3
SMFF			1	3	2
SH				1	1/2
SF					1

SMS: Stamping. MC: Casting. SMFF: Fold Forming. SH: Sheet Hydroforming. SF: Superplastic Forming.
↑: Increasing. ↓: Decreasing

Rule Based Reasoning for IAHP

RBR is used to establish the logical component of IAHP. The sequence of IF-THEN rules triggers the needed logic to evaluate the content of knowledge bases in addition to user's feedback. The major reasoning files followed to execute the analysis are represented in Figure 6.8. Each execution step or file contains set of rules that address a certain knowledge base and certain piece of information within each individual knowledge base.

One major step in IAHP is the inconsistency check; where the inconsistency parameter is a measure of the internal uniformity or homogeneity of the relative importance values entered into the evaluation matrices. The RBR logic is trained to inspect the inconsistency value for each matrix formed during CEA and CEC steps, where the value should not exceed 10%. Hence, the system is trained to reject any evaluation values resulting with inconsistency greater than 0.01 then advice the user to revisit the evaluation and modify the values.

The final results of the IAHP will be the actual ranking of the alternative manufacturing process that best can be selected as a major fabricating procedure for BiW panels. The ranking takes into consideration the production requirements as extracted from process attributes, where the later are concluded from direct customer requirements.
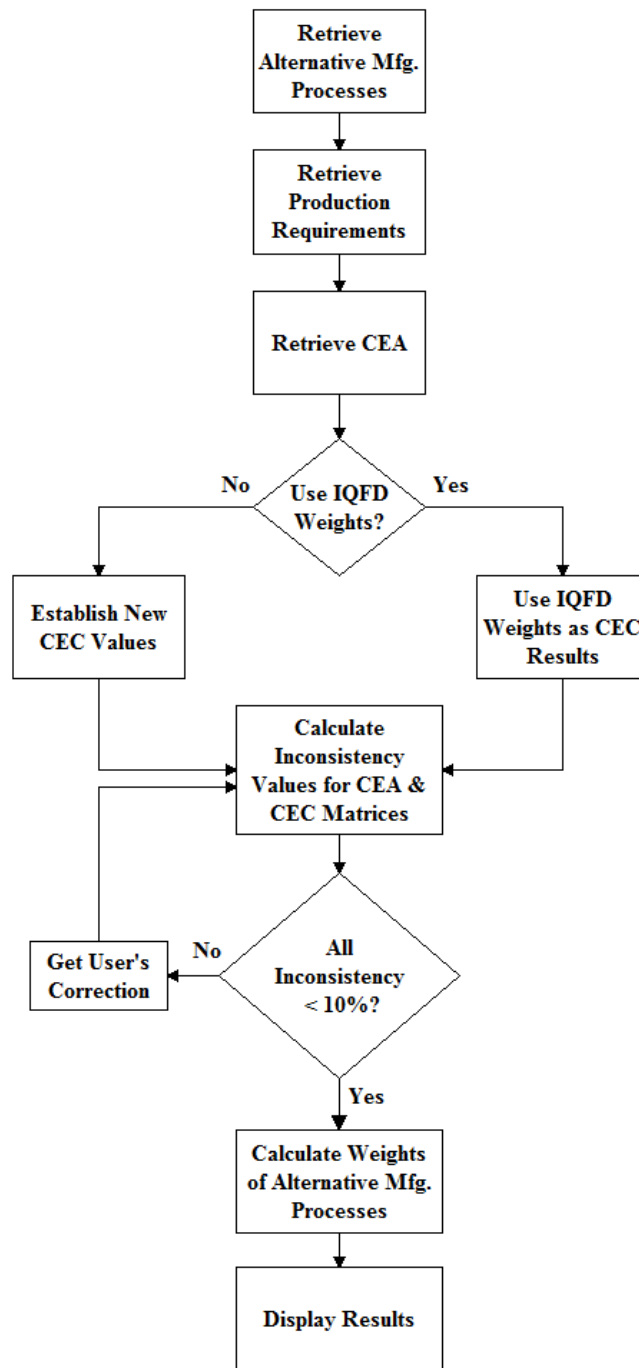
Figure 6.8 The sequence of RBR logic files for IAHP analysis.

6.3.3 Graphical User Interface (GUI)

In addition to knowledge bases and reasoning logic, the GUI is the third component that packages the content of IQFD and IAHP modules. The GUI displays all results in graphical form, specifically charts and tables, which easily express the effect of production requirements on process attributes in IQFD phase. The graphical results also directly indicate the performance of each candidate manufacturing process towards achieving the selection goal in IAHP. The suitable representation of results is a key advantage of the developed KBS in this work.

The GUI is web-based in nature, hence the results are displayed in a sequence of webpages that contain the results' charts and tables, the webpages hold general figures that summaries the analysis's steps as well. The ability to publish the analysis and results of KBS in a web-based form increases the utilization and proficiency of the developed KBS, where the user can easily access the system's results and modify the knowledge bases contents. In addition to the ability to use webpages editors to customize the look and fashion of the GUI decreases the development time for KBS.

6.4 Case Study

The KBS developed in this work is used to perform a case study for automotive production line design. The purpose of this design task is to select a manufacturing process automotive production line that meets the main production requirements, where those production requirements are translated directly from process attributes. The production requirements and process attributes are extracted from the needs of BiW

panels, however they do not represent a specific design needs for a certain BiW panel type.

Upon launching the system, the first webpage, shown in Figure 6.9, asks the user to input the case information into the system, the ability to store all previous conducted design cases enables the user to easily retrieve them upon request.

Figure 6.9 First webpage of the developed KBS.

Following pages initiates the user's interaction with the IQFD component, the user is promoted to select process attribute from knowledge base content and add new ones with their customer importance rating as shown in Figure 6.10. In this case study, we selected process attributes for BiW panels that are initially stored in the knowledge base with the customer importance weights illustrated previously in Table 6.1. The

process attributes stored in the database are extracted from the design needs of BiW panels.

Afterwards, the KBS leads the user to the production requirement webpage, where the designer selects the suitable production requirements by examining the production requirements stored in the knowledge base with the ability to add new production requirements to the analysis. Figure 6.11 displays the webpage for second stage of IQFD analysis and the selected production requirements for the case study, where all production requirements included in the case study analysis are those initially stored in the knowledge base.

Figure 6.10 Selecting the process attributes and their customer importance rating from IQFD knowledge base.

The selected process attributes and production requirement are not dedicated to a specific BiW panel type or a certain panel from the sets of BiW panels, rather the production requirements represent the needs that should be satisfied when designing a production line for automotive panels, the benefits of using KBS to perform such task is the ability to store the experience used to judge and design a production line through all stages of design, hence the user can use all available knowledge previously used and modify the task of design based on current conditions.

When the correlation is established, the route of IQFD logic displays two options for the user; the first is to use the correlation values stored in the knowledge bases, while the second offers the option to create new ones. The KBS directs all new entered values to the corresponding knowledge base to be used in future cases and to the previous cases retrieval. For the case study purpose, we select the "Use Stored Knowledge" option shown in Figure 6.12.

Figure 6.13 demonstrates the retrieved correlations values for the assigned process attributes and production requirements; the system organizes the values into a table format. The final targeted weights are displays in the final stage of IQFD analysis, the production requirements are assigned targets weights towards the achievements of process attributes, and Figure 6.14 exhibits the results of IQFD phase for the case study. The top three major production requirements of the case study that contribute greatly to the listed process attributes of BiW panels are consolidation of parts, reducing in number of components and avoiding intricate shapes.
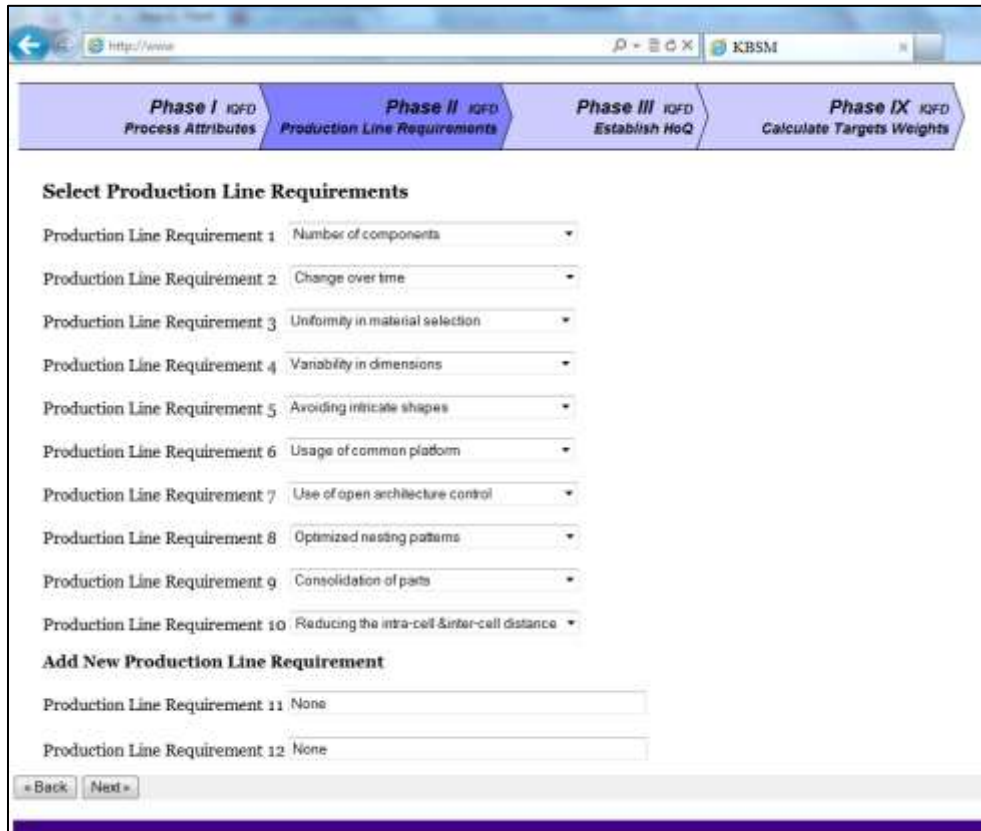
Figure 6.11 Selecting the production requirements.
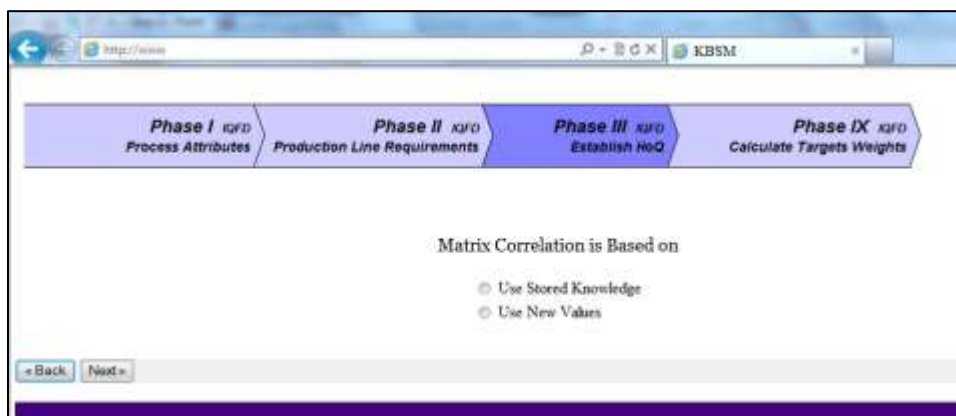
Figure 6.12 The two built options for correlation establishment in IQFD.

	Number of components	Change over time	Uniformity in material selection	Variability in dimension	Avoiding intricate shapes	Usage of common platform	Use of open architecture control	Optimized nesting patterns	Consolidation of parts	Reducing the intra-cell /inter-cell distance
Reduction in lead time	9	3	3	3	3	3	1	3	9	9
Fewer operations	9	9	9	9	9	3	1	3	9	1
Reduction in operational complexity	1	1	9	9	9	3	1	3	1	1
Standardization	1	3	9	9	3	9	1	3	9	1
Ease of reconfiguration	3	1	3	3	3	9	9	3	3	9
Automation	9	1	3	3	1	9	9	1	3	9
Scrap reduction	3	1	1	1	3	3	1	9	3	1
Decrease in rework	3	1	1	1	3	1	1	9	3	1

Figure 6.13 Stored correlations values as retrieved from the knowledge base for the set of process attributes and production requirements for case study.

The system directs the user to the IAHP component of the KBS after displaying IQFD final results; with the first webpage of the IAHP component asks the user to set the IAHP hierarchal parts, and then displays the overall hierarchy structure for selecting a manufacturing process for the production line based on the rated requirements of the BiW panels, the objective of this phase is to identify the manufacturing process that can achieve most of the highly rated production requirements, the data base of manufacturing process also included the characteristics of the fold forming process. Figure 6.15 illustrated the structure of the IAHP phase; the system lists the selected production requirements and the available manufacturing process. In addition, the case study uses IQFD results for CEC value.

The initial webpage contains the options for the user to assign CEC final values; two routes are available in KBS ; either to user IQFD target weights for production

requirements, or conduct new CEC. Then, the system retrieves the stored CEA for the list

of production requirements and displays the values as table form, Figure 6.16.

The next step is the CEC for production requirements. For the case study, the results of

IQFD are used as priority weights for comparative criteria; Figure 6.17 shows the

graphical results of CEC step produced for the case study.

Final Target Weights of IQFD

Production Requirements	Target Weights	Normalized Target Weights
Number of components	261.00	11.82
Change over time	213.00	9.65
Uniformity in material selection	231.00	10.46
Variablity in dimensions	231.00	10.46
Avoiding intricate shapes	249.00	11.82
Usage of common platform	237.00	10.73
Use of open architecture control	141.00	6.39
Optimized nesting patterns	159.00	7.20
Consolidation of parts	273.00	12.36
Reducing the intra-cell &inter-cell distance	213.00	9.65

IQFD Results (Target Weights)

Legend: Decrease in rework, Scarp reduction, Automation, Ease of reconfiguration, Standarization, Reducing operational complexity, Fewer operations, Reduction in lead time
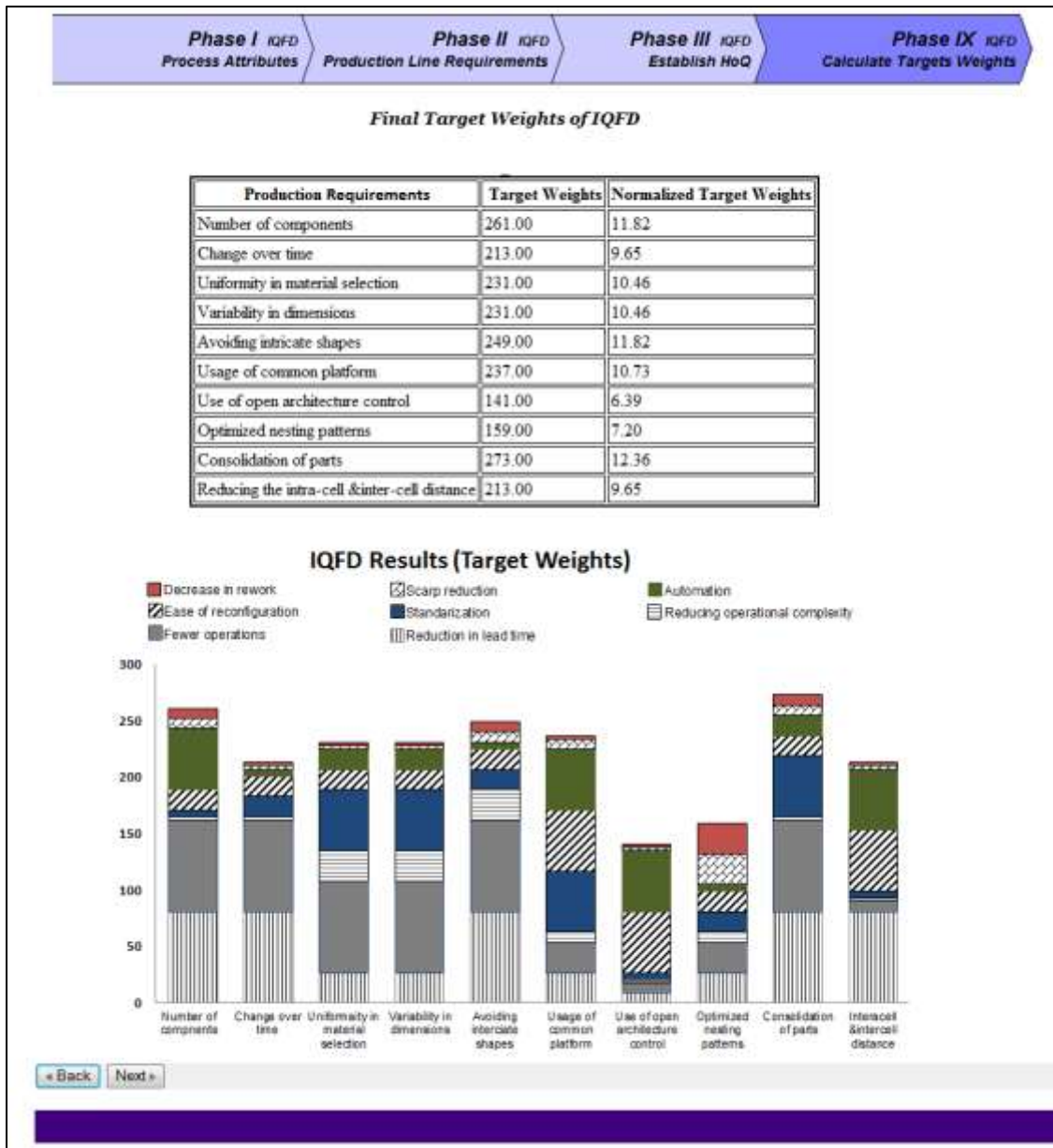
« Back   Next »

Figure 6.14 Results of IQFD phase for case study.
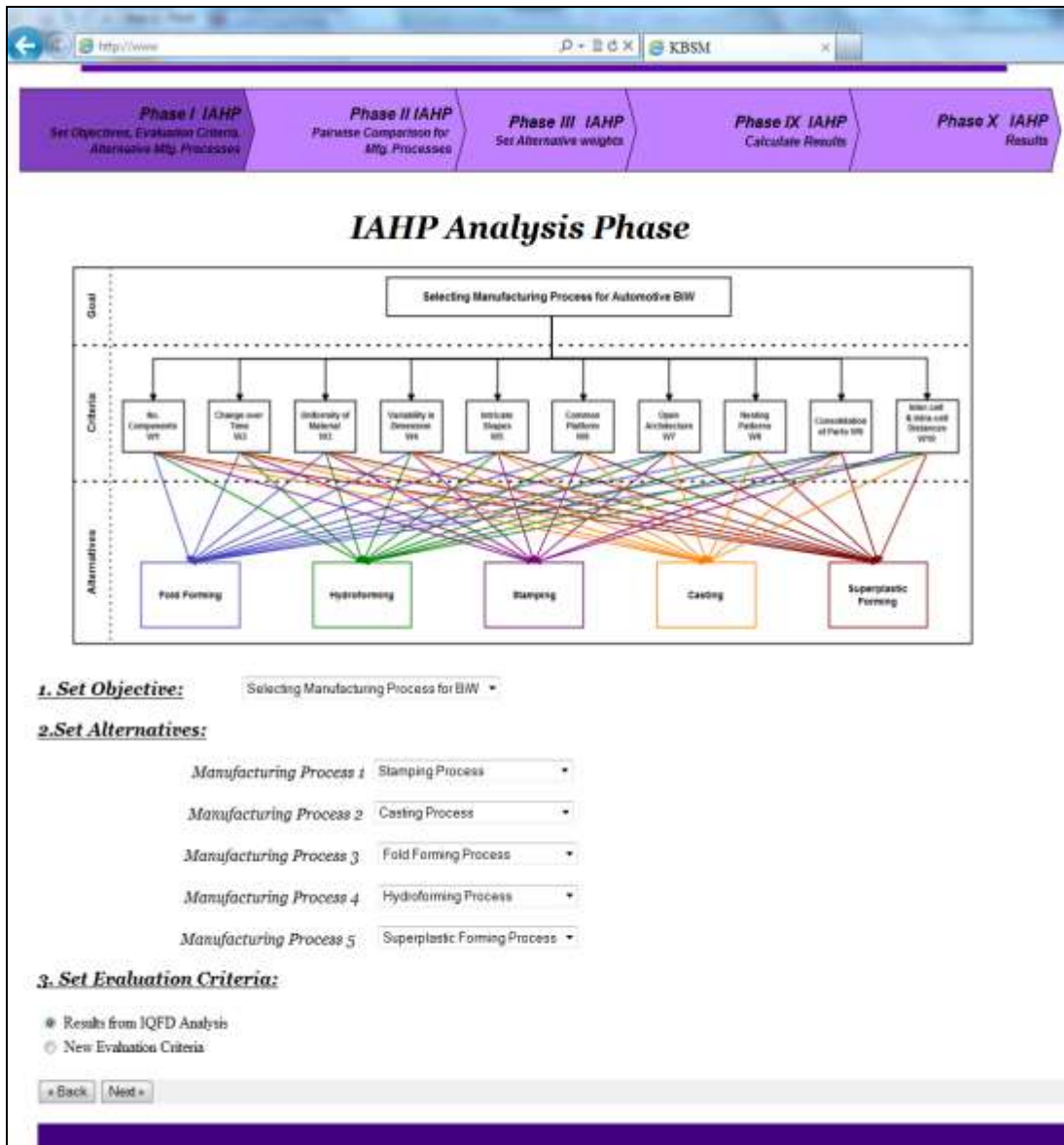
Figure 6.15 The hierarchy structure of IAHP analysis for case study.
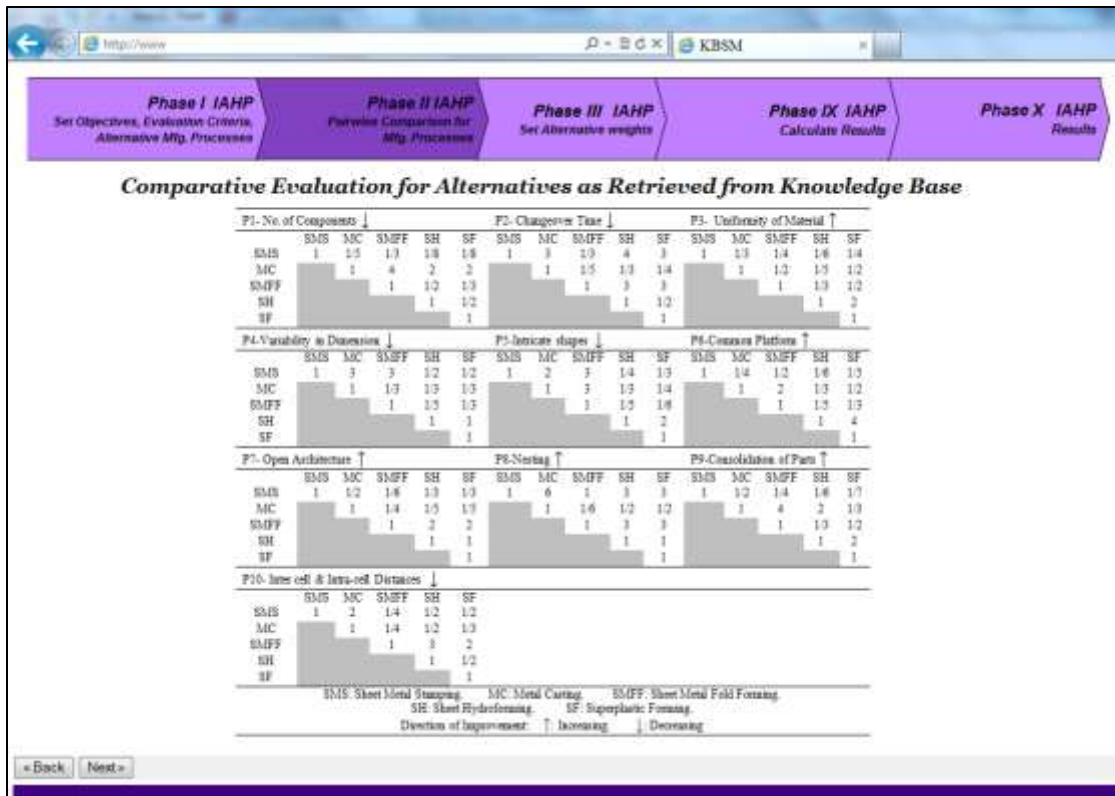
Figure 6.16 CEA values for case study.
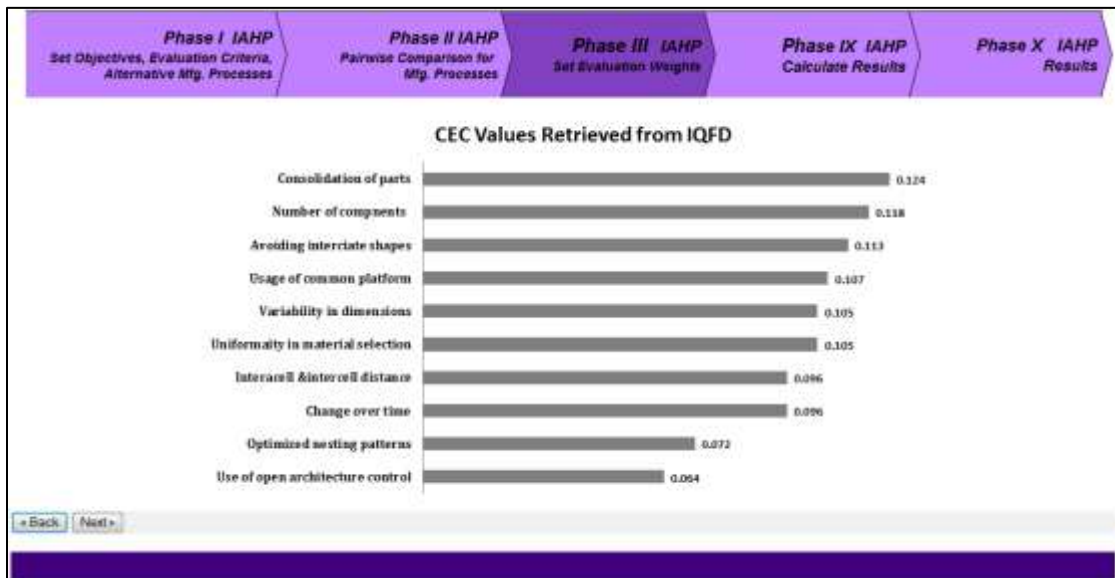
Figure 6.17 CEC values as retrieved from IQFD analysis for case study.

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Up to this point, the KBS contains all required information to rate the selected manufacturing processes in terms of the production requirements that are extracted from the needs of automotive production line, the final step is to check inconsistency condition and calculate the final ranking. Figure 6.18 indicates the results for IAHP phase of KBS for the case study.

The outcome of the IAHP, Figure 6.18, indicates that in terms of the production requirements selected along with their ranking the manufacturing process that can comply with the ranked production requirements is SF and SH, while SMFF achieved better position than regular SMS in terms of those production requirements. It should be noted that the ranking of manufacturing process is subjective and related to accomplishing the selected production requirements and their corresponding target weights; hence SF and SH processes scored the highest rank for the design case for the specific production requirement list and their weights based on the production line needs stated in the IQFD results. Moreover, the system can be used to investigate the selection of a manufacturing process based on a single BiW panel type or design requirements if those are selected in the production requirements phase.

The objective of the KBS built in this work is to route the design of a production line in a backwards manner, the traditional approaches is to select a manufacturing process then design the production line according to it, rather the KBS developed here aims at exploring the manufacturing processes by starting with the production line requirements, then investigate the possibilities to modify these manufacturing process to

fit the production line in what can be termed as systems manufacturing . One of the main contributions to this tool is to rate the fold folding process relative to the traditional manufacturing process with respect to specific production line requirements. As the KBS grows the databases can include more traditional and new technologies emerging, which serve as an evaluation tool with accumulated experience and knowledge for a production line
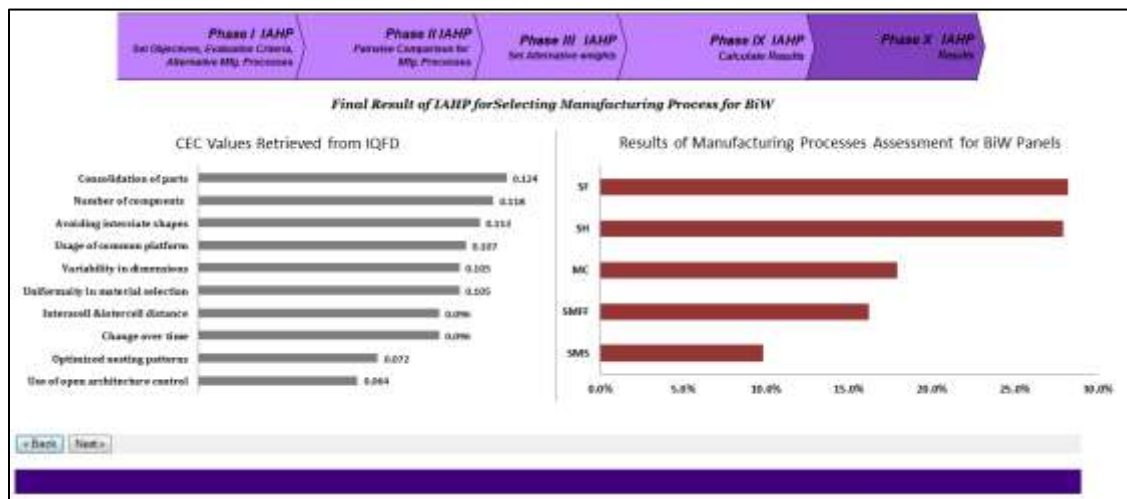
Figure 6.18 Final results of case study.

6.5   Summary

The work in this chapter employed a comprehensive knowledge-based system to design a production line and provide an evaluation tool for fold forming process with respect to other available manufacturing processes, where the essential process attributes are fed into an IQFD phase to recognize and analyze the major production requirements that can best translate customer needs when designing a production line for BiW panels. Then the production requirements are employed in IAHP to assist in manufacturing process selection that best achieve the highest performance of each production

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requirement. The KBS is able to translate customer needs into one aspect of production line design; that is the selection of manufacturing process, by applying HoQ and AHP principles into an expert system.

The incorporation of KBS with QFD and AHP principles increases the efficiency of design procedure and reduced time requirements, it also provided ready to use tool that is directly linking the customer needs with candidate manufacturing processes for a production line of BiW panels.

Finally, the system is packaged in a web-based user interface which made the system user friendly and enables it to represent the system's findings numerically and graphically as well.

CHAPTER SEVEN

CASE STUDIES

7.1   Introduction

This chapter contains four case studies that mainly include automotive components; vehicles' interior, front module, battery enclosure for electrical vehicle and a second floor panel design. The analysis starts with the FPA and its accompanying optimization metrics. Whereas, the second phase involves analyzing the stressed-based performance of these components under predefined static loading conditions, subsequently the study conducts the optimization analysis for composite material.

7.2   Batteries Enclosure for Electrical Vehicle

7.2.1   FPA

The second metallic part is the battery pack for an electric vehicle; the part is composed of three different components to facilitate the assembly and disassembly of batteries. Figure 7.1 illustrates the batteries enclosure with its components. The FPA results are listed in Table 7.1
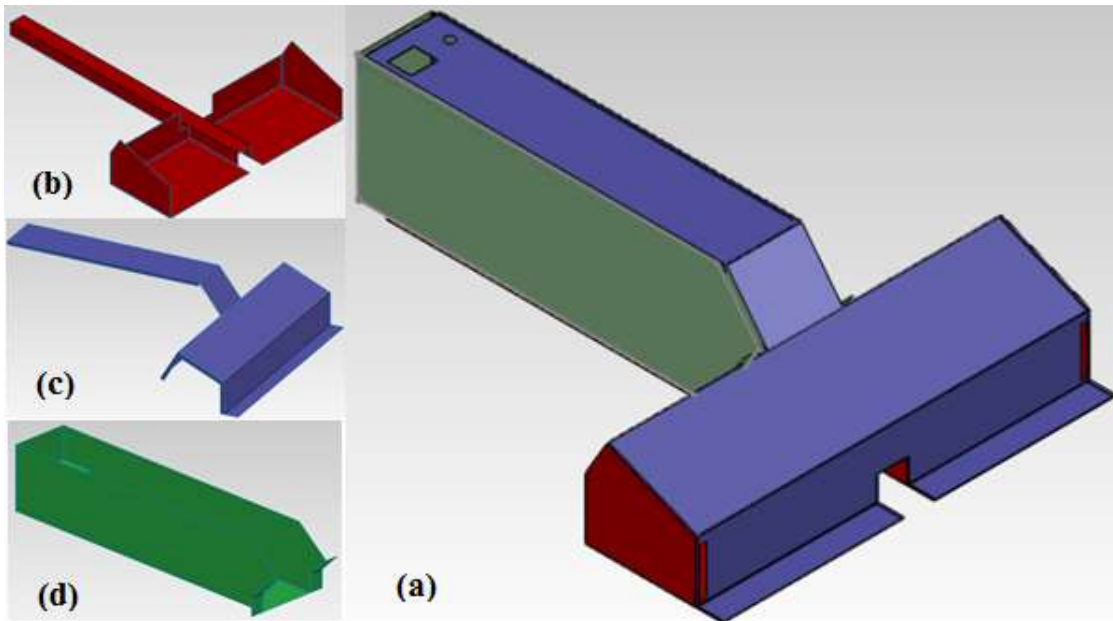
Figure 7.1 (a) Batteries enclosure with its components. (b) component one. (c) Component two. (d) Component three.

Figure 7.2 Batteries enclosure for electrical vehicle.
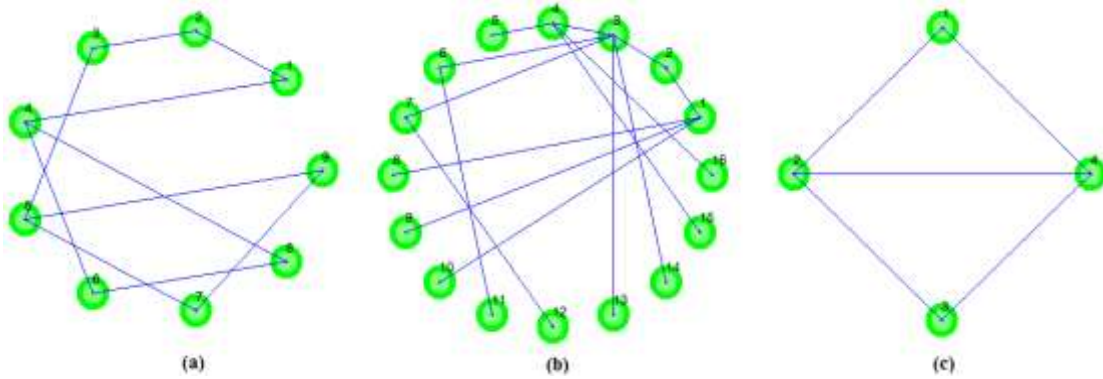
Figure 7.3 (a) FAG of component-b of batteries enclosure. (b) FAG of component-c. (c)

FAG of component-d of batteries enclosure.

Table 7.1 FPA summary results for batteries enclosure part.

Component	No. of Faces	No. of Edges	No. of Topologically Valid Spanning Trees	No. of Geometrically Valid Flat Patterns
Comp(b)	9	10	9	9
Comp(c)	16	15	1	1
Comp(d)	4	5	8	8

The actual metallic enclosure is presented in Figure 7.2, the three different components are joined by riveting, while the accompanying FAGs are illustrated in Figure 7.3. The first component had nine topologically valid spanning trees, as listed in Figure 7.4, all of those spanning trees successfully generated a flat pattern with no overlapping. Each of the spanning trees resulted with valid flat pattern, the generated flat pattern for each of the spanning trees are shown in Figure 7.5, where the dimensions is in mm.

For component-c, the upper part of batteries enclosure, there is only one valid spanning tree that generated a geometrically valid flat pattern; Figure 7.6 represents the

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spanning tree and its corresponding valid flat pattern for component-c. The final third component of batteries enclosure has eight valid spanning trees displayed in Figure 7.7, while the flat patterns are shown in Figure 7.8.

The results of optimization metrics for battery enclosure components are listed in Table 7.2. For component-c there is only on feasible flat pattern, hence it is considered the optimal in terms of all metrics.
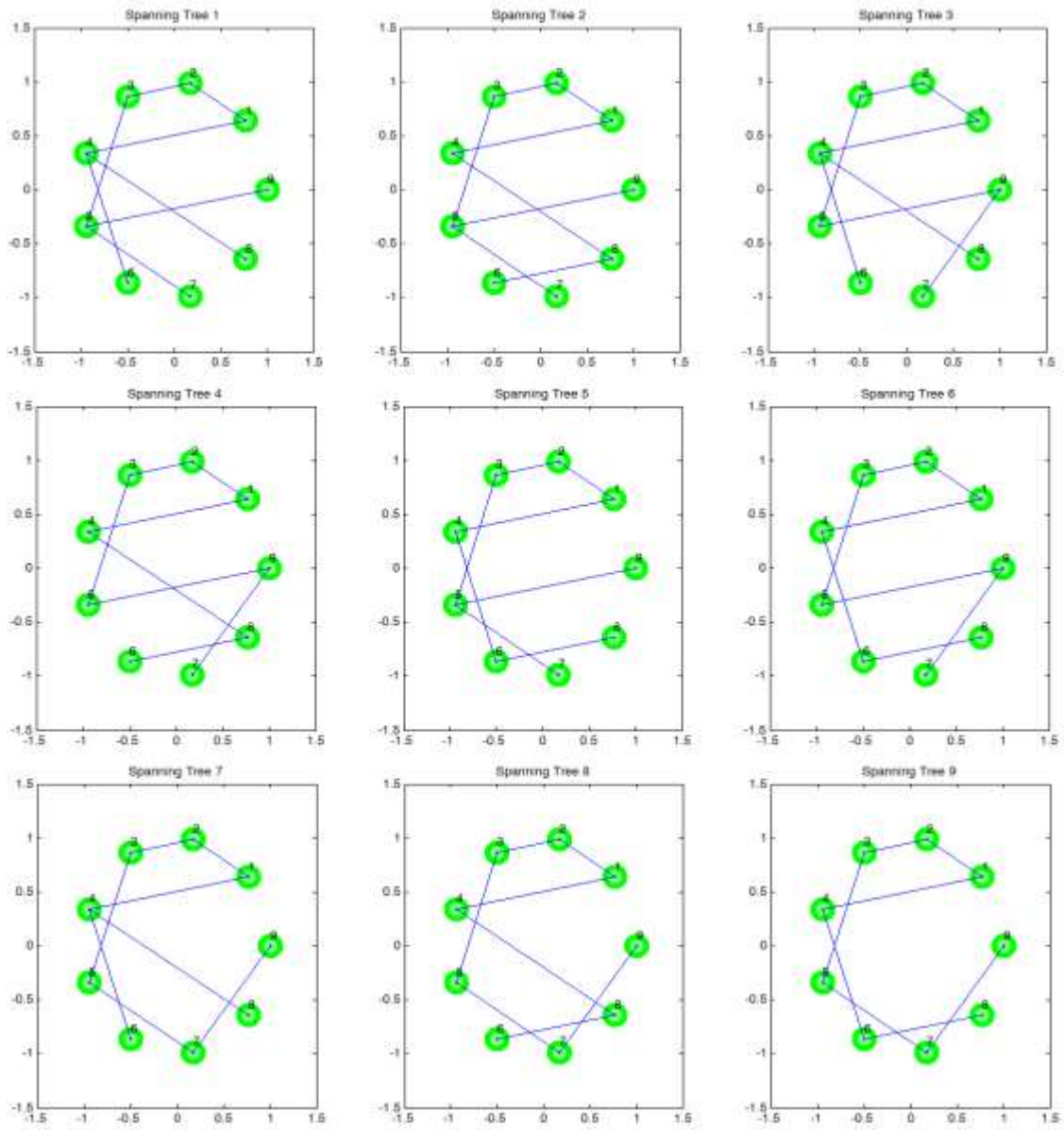
Figure 7.4 Spanning trees of component-b for batteries enclosure.
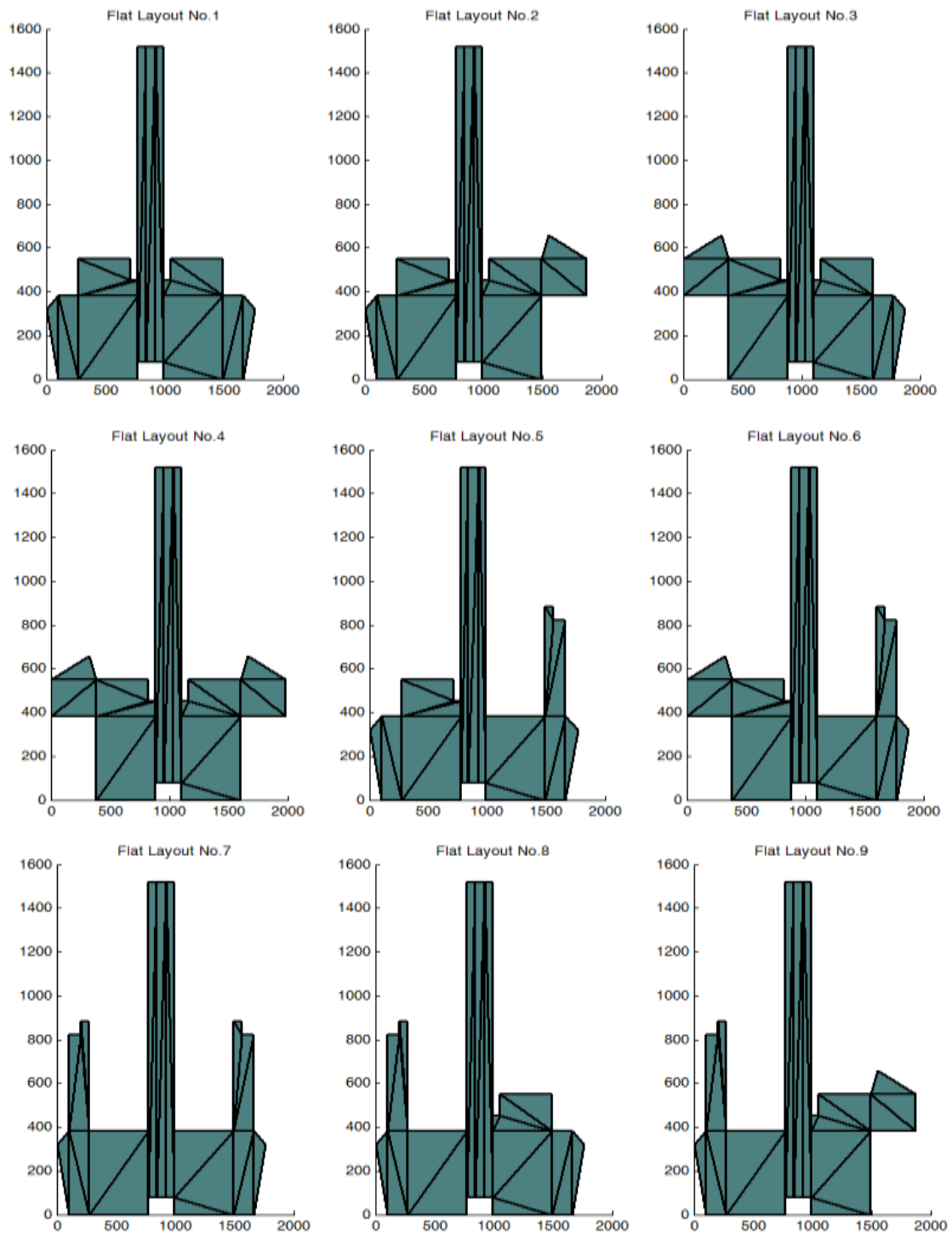
Figure 7.5 Flat patterns of component-b of batteries enclosure.
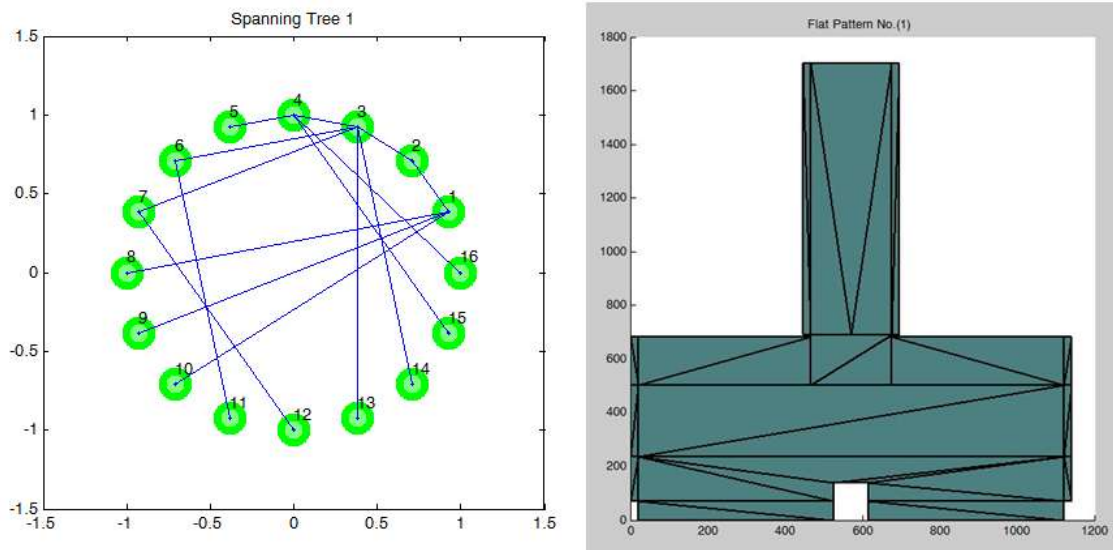
Figure 7.6 Spanning tree and flat pattern for component-c of batteries enclosure.
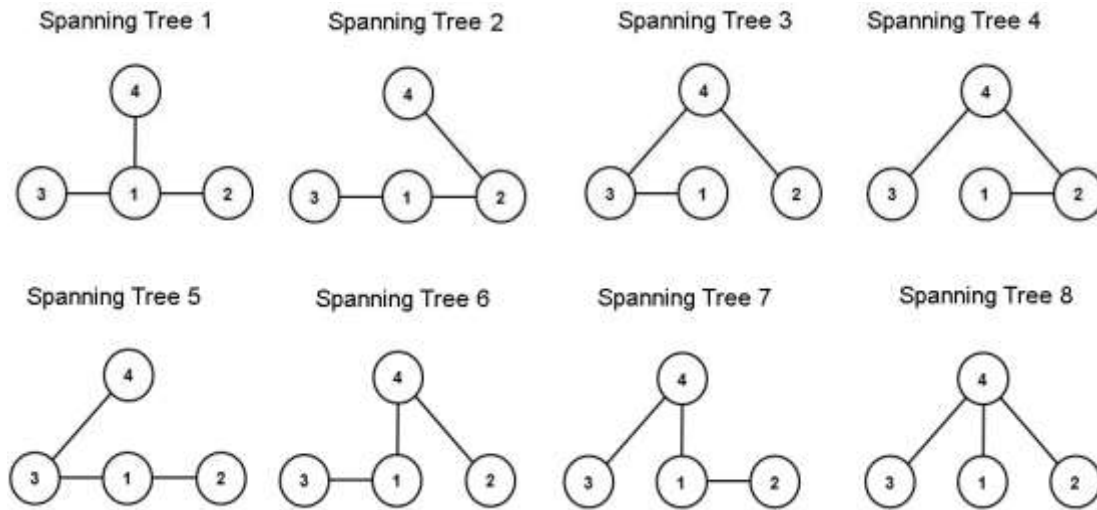
Figure 7.7 Valid spanning tree for component-d of batteries enclosure.
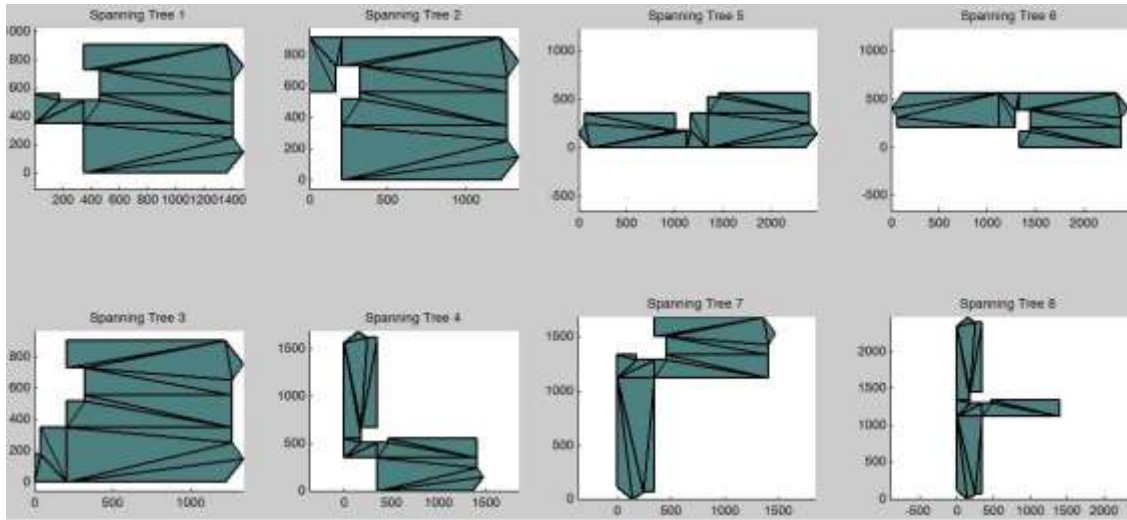
Figure 7.8 Flat patterns of component-d of batteries enclosure.

Table 7.2 Results of applying optimization metrics for battery enclosure part.

Comp. Figure	CM Geometric	CM min .OverallExtent	CM min. EnclosingArea	CM Area Condensation	NEM	NBM	OBM	WCM
(b) 7.13	Pattern 1	Pattern 1,5,7,8	Pattern 1,5,7,8	Pattern 1,5,7,8	Pattern 7	All equal; 8 bends	Pattern 1,7	Pattern 1
(c) 7.14	Pattern 1	Patterns 1	Pattern 1	Pattern 1	Pattern 1	Pattern 1	Pattern 1	Pattern 1
(d) 7.15	Pattern 3	Pattern 2,3	Pattern 2,3	Pattern 2,3	Pattern 5,6	All equal; 3 bends	All are equal	Pattern 3

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7.2.2 Stress-Based Ranking

The battery enclosure is made up of aluminum sheets with 0.002 m thickness. In order to apply the stress-based ranking, the first step is to examine the geometry of the battery enclosure by labeling all vertices as shown in Figure 7.9, the list of forces applied on the battery enclosure are also indicated on each of the vertices. The total elements that are connecting the various vertices are equal to 58 elements. While the magnitude and direction of each of the applied forces is listed in Table 7.3.
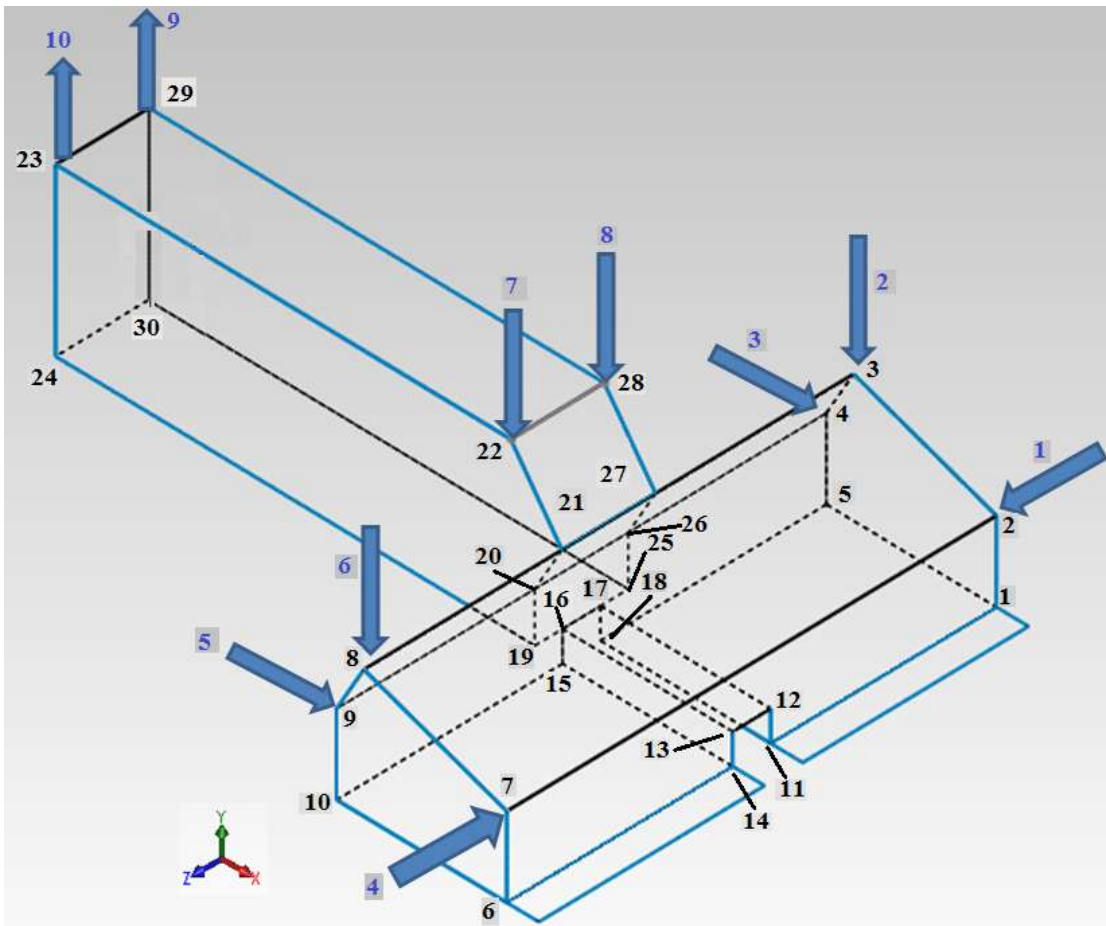
Figure 7.9 Stress-based ranking analysis of battery enclosure part.

Table 7.3 Magnitude and direction of applied forces on battery enclosure part.

Node	Direction	Force (N)
2	Z	5,000
3	Y	-10,000
4	X	1,000
7	Z	-5,000
8	Y	-10,000
9	X	1,000
22	Y	-5,000
23	Y	10,000
28	Y	-5,000
29	Y	10,000

In the first phase of the analysis, each structural element is considered to have the same stressed-based properties, i.e. the stiffness factor is not modified to account for the classification of elements into weld, fold, or face elements. The resulted axial stresses in such case are listed in Table 7.4 below. It can be seen that some elements are under high axial stress compared to zero stress elements, the best flat pattern design in terms of stress-based ranking is the design that classifies the high stress elements as weld structures, while the zero stress elements are preferable categorized as fold lines, since the fold line is anticipated to be the weakest in loading bearing due to the material discontinuities along the fold line. The second step is to classify elements with indicating those which can be fold or weld lines depending on the selected design of flat pattern. Table 7.5 highlights the element type for each of the elements in battery enclosure structure.

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Table 7.4 Axial stress in element structure of battery enclosure with no modification for

stiffness factor.

Element	Axial Stress (kPa)	Element	Axial stress (kPa)	Element	Axial Stress (kPa)
1	-813	21	-525	41	0
2	-2,613	22	2,505	42	0
3	-4,877	23	-570	43	0
4	-3,956	24	0	44	5,000
5	0	25	0	45	0
6	-793	26	0	46	0
7	-2,595	27	0	47	0
8	-4,883	28	0	48	0
9	-3,994	29	0	49	0
10	0	30	0	50	0
11	0	31	0	51	0
12	-2,500	32	0	52	0
13	59	33	0	53	-730
14	59	34	0	54	-1,942
15	0	35	-420	55	-531
16	59	36	-457	56	-2,378
17	-61	37	0	57	0
18	-59	38	5,000	58	0
19	-59	39	0		
20	2,471	40	0		

Table 7.5 Classification of elements types for each element in battery enclosure structure.

Element	Type of Element	Element	Type of Element	Element	Type of Element
1	Weld	21	Face	41	Weld
2	Weld	22	Face	42	Weld
3	Weld	23	Face	43	Weld
4	Weld/Fold	24	Weld	44	Weld/Fold
5	Weld/Fold	25	Weld	45	Weld/Fold
6	Weld	26	Weld	46	Weld
7	Weld	27	Fold	47	Face
8	Weld	28	Weld	48	Face
9	Weld/Fold	29	Weld	49	Weld
10	Weld/Fold	30	Weld	50	Weld/Fold
11	Weld	31	Fold	51	Face
12	Fold	32	Fold	52	Face
13	Fold	33	Fold	53	Face
14	Weld	34	Weld/Fold	54	Face
15	Weld/Fold	35	Weld/Fold	55	Face
16	Face	36	Weld	56	Face
17	Face	37	Weld	57	Face
18	Face	38	Weld	58	Face
19	Face	39	Weld		
20	Face	40	Weld		

It can be noticed that there are ten total elements that can be assigned as either fold or weld lines, hence to select the flat patterns design for each component we need to select those patterns, where the fold lines are experiencing minimal axial force, and as a result minimal axial stress occurs that can lead to failure along the fold line. Table 7.6 indicates the optimized combination of weld and fold lines for the ten elements discussed previously.

Table 7.6 Optimized combination of weld and fold lines for best stress-based ranking of battery enclosure part.

Element	Assigned Type
4	Weld
5	Fold
9	Weld
10	Fold
15	Fold
34	Fold
35	Weld
44	Weld
45	Fold
50	Fold

The assigned combination shown in Table 7.6 is feed to the structural analysis to determine the anticipated axial stress in each of the elements besides the modification for stiffness factors to accommodate the elements various types. The resulted axial stresses in each of the structure elements are listed in kPa in Table 7.7. It can be seen that the axial stress remained the same or is reduced in each of the ten elements under study. The minimal changes in axial stress are due to the modification of some elements by

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increasing the their stiffness as weld lines, while decreasing the stiffness factor of fold lines did not affect the axial stress with increase since the external forces are distributes heavily among the stronger elements i.e. weld and face lines. Figure 7.10 displays the flat patterns for batteries enclosure based on the results of the stress-based ranking for the three components.
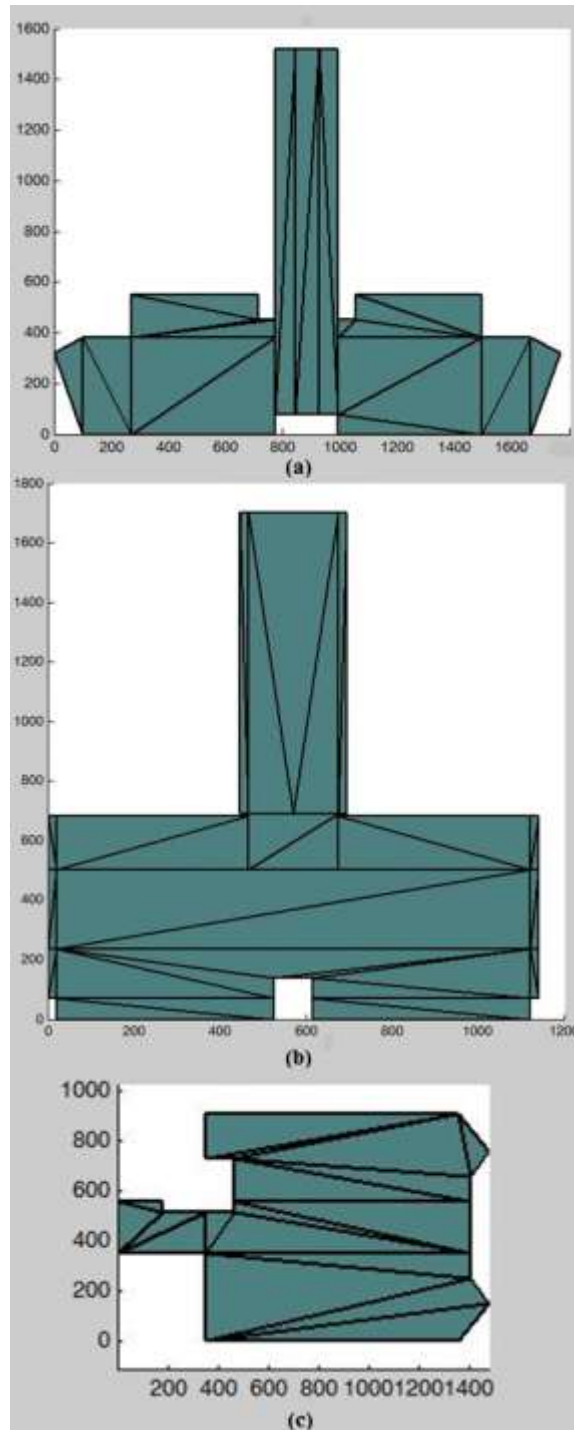
Figure 7.10 Resulted flat pattern for stress-based ranking of battery enclosure. (a) Flat pattern of component-b. (b) Flat pattern of component-c. (c) Flat pattern of component-d.

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Table 7.7 Resulted axial stresses in battery enclosure elements after stiffness factor

modification based on element type.

Element	Axial stress (kPa)	Element	Axial stress (kPa)	Element	Axial stress (kPa)
1	-810	21	-530	41	0
2	-2,613	22	2,502	42	0
3	-4,878	23	-565	43	0
4	-3,961	24	0	44	5,000
5	0	25	0	45	0
6	-794	26	0	46	0
7	-2,599	27	0	47	0
8	-4,883	28	0	48	0
9	-3,990	29	0	49	0
10	0	30	0	50	0
11	0	31	0	51	0
12	-2,500	32	0	52	0
13	45	33	0	53	-744
14	45	34	0	54	-1,911
15	0	35	-449	55	-531
16	46	36	-490	56	-2,378
17	-47	37	0	57	0
18	-46	38	5,000	58	0
19	-46	39	0		
20	2,475	40	0		

7.2.3 Composite Material Analysis

The type of composite material selected for battery enclosure is Type I carbon/epoxy, where the elastic constants, values of strength properties and applied principle stresses are listed below in Table 7.8 (Hull 1987).

The results for best fiber orientation are shown in Figure 7.11; under the stated applied stresses the Type I carbon/epoxy laminate of battery enclosure exhibits the

highest modules of elasticity when fibers are positioned with 0° with 33.77 GPa for E, while 60° fiber orientation achieved the second rank. However, these values should be evaluated simultaneously with the ultimate stress test, where the resulted principle stresses are inspected to makes sure the material will withstand the applied stress and will not fail. Table 7.9 lists the outcomes of inspection for battery enclosure case; accordingly the fiber can be positioned with 0, 50, and 60 degrees only while the rest of orientation can weakens the structure.

Table 7.8 Inputs for composite material analysis of battery enclosure part.

Elasticity Constant	Value
V_f	50%
E_m	2.415 GPa
E_f	138 GPa
E_1	220 GPa
E_2	8 GPa
G_{12}	64 GPa
Strength Properties	MPa
$(\sigma_1^T)_{ult}$	1100
$(\sigma_1^C)_{ult}$	900
$(\sigma_2^T)_{ult}$	40
$(\sigma_2^C)_{ult}$	190
$(\tau_{12})_{ult}$	75
Applied Stress	MPa
σ_x	90
σ_y	30
τ_{xy}	5

Figure 7.11 Resulted composite material modulus of elasticity for each possible fiber

orientation (θ) of a lamina of battery enclosure part.

Table 7.9 Outcome of ultimate strength values test for each of the fiber orientation case.

The second parameter in composite material analysis is the total length of weld lines, the application of Prim's algorithm for all FAG of each component resulted with the flat patterns shown in Figure 7.13, where the total length of weld lines is the minimum among all other combination of flat patterns for the battery enclosure part. Lastly, the adhesively joined links are revised to take into consideration the direction of peel shear with respect to fiber orientation at the surface ply of the battery enclosure. The selected fiber orientation is 0° which leads to minimal number of edges subjected to peel shear that is perpendicular to fiber orientation.
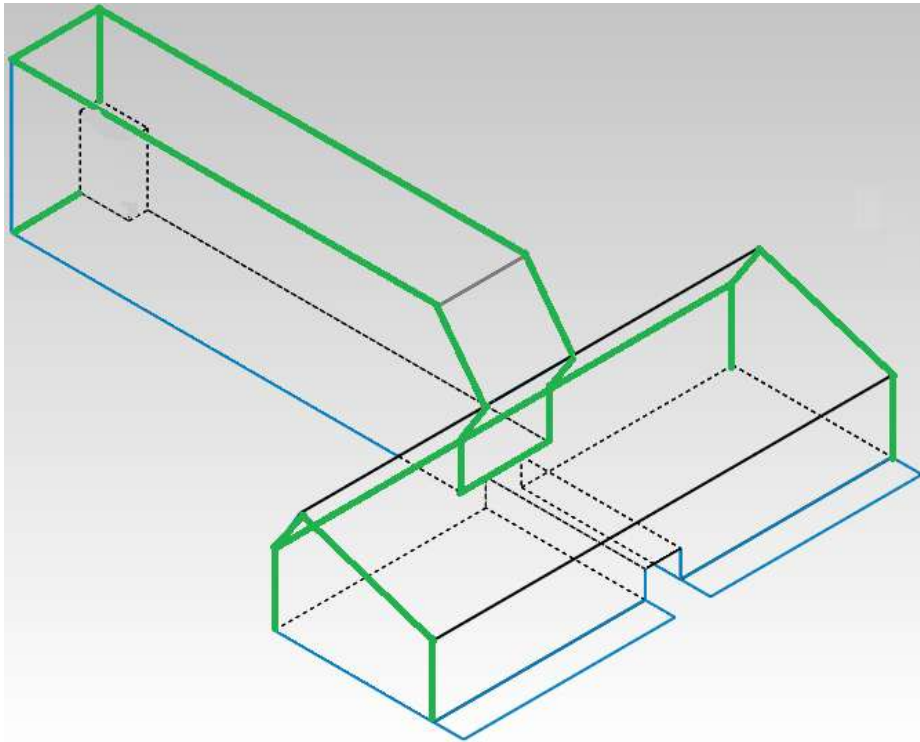

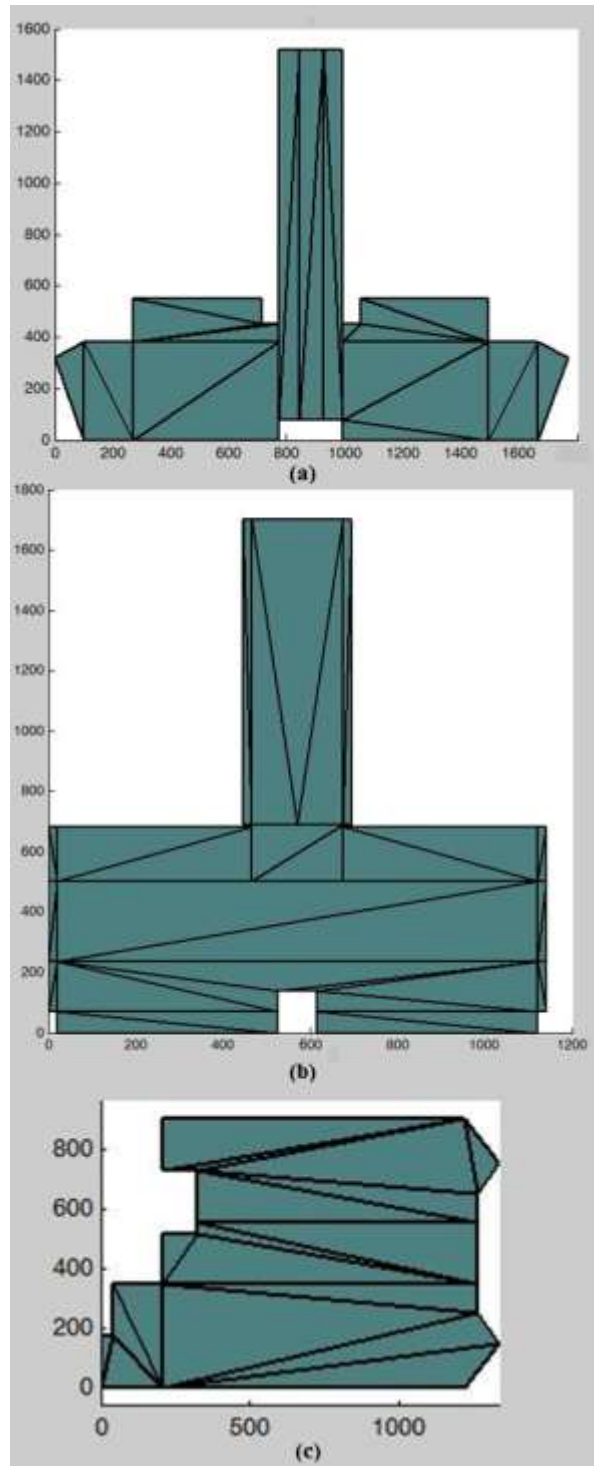Figure 7.12 The seam lines for the battery enclosure component.

Figure 7.13 Flat pattern designs that exhibit the least total length of welds for battery
enclosure component.

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7.3   Vehicle's Interior

The design investigated for vehicle's interior is shown in Figure 7.14, the design is composed of two main components; the first is the dashboard while the second the floor panel with the center console. Table 7.10 summarizes the topological features of the two components in terms of number of faces and number of edges, the table also includes the results of FPA as number of topologically valid spanning trees. The FAG has been used as an input for the enumeration algorithm in the FPA phase as displayed in Figure 7.15, while some of the spanning trees for the floor panel and the center console are also shown in Figure 7.16.

Table 7.10 Topological features of vehicle's interior.

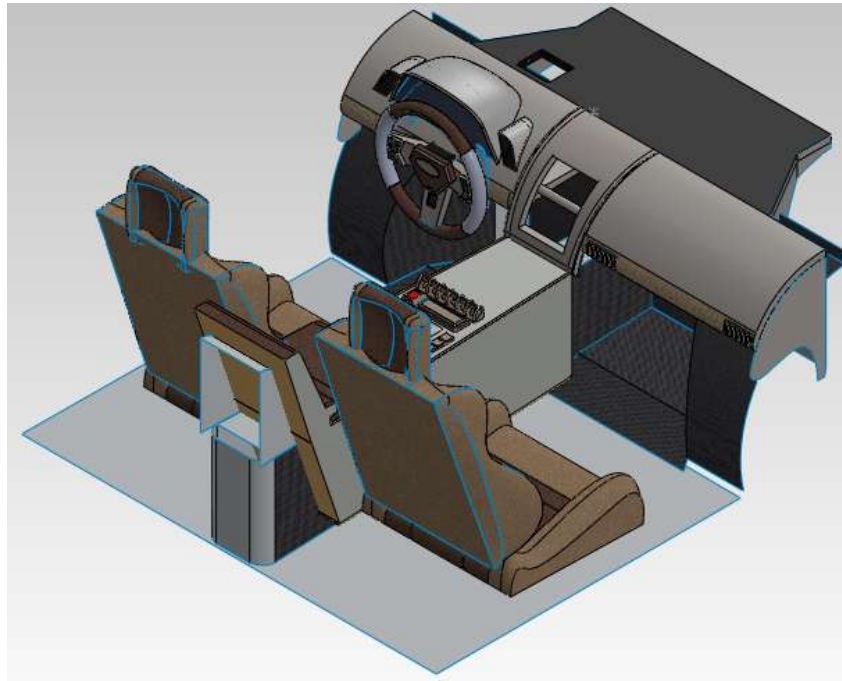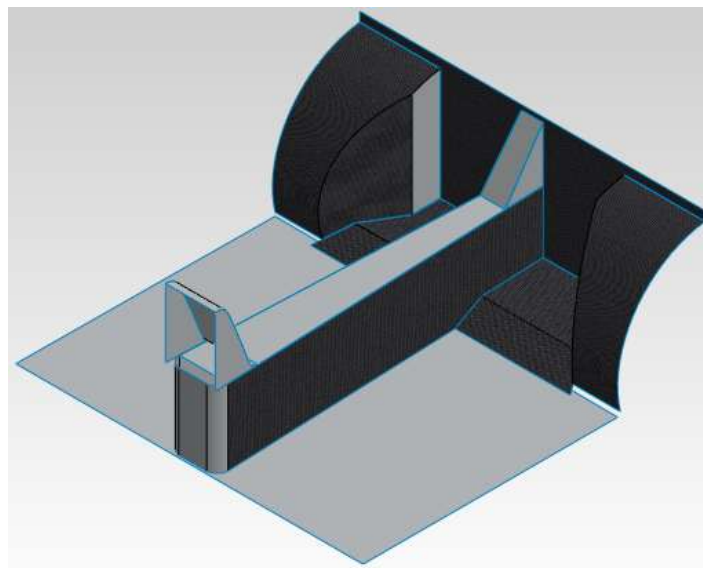| Component	No. of Faces	No. of Edges	No. of Topologically Valid Spanning Trees	No. of Geometrically Valid Flat Patterns
Dash Board	8	6	15	1
Floor Panel & Center Console	15	26	94,864	9

Figure 7.14 Vehicle's interior.

Figure 7.15 Floor panel and center console of vehicle's interior.

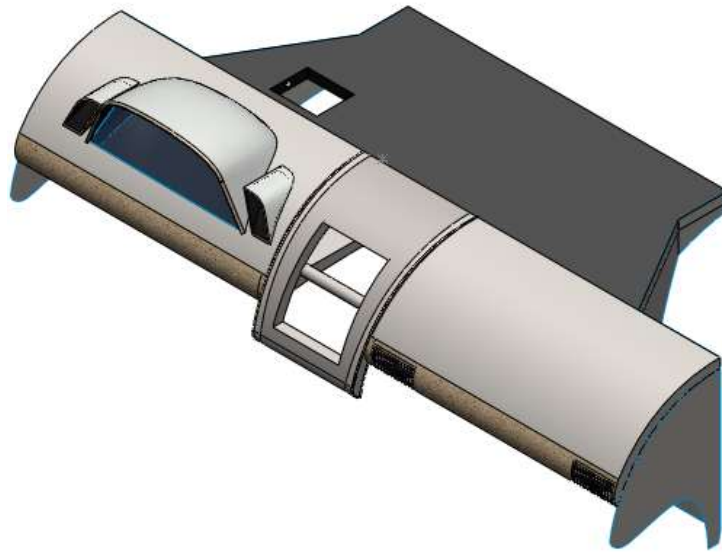Figure 7.16 Dashboard component of vehicle's interior.

(a)   (b)
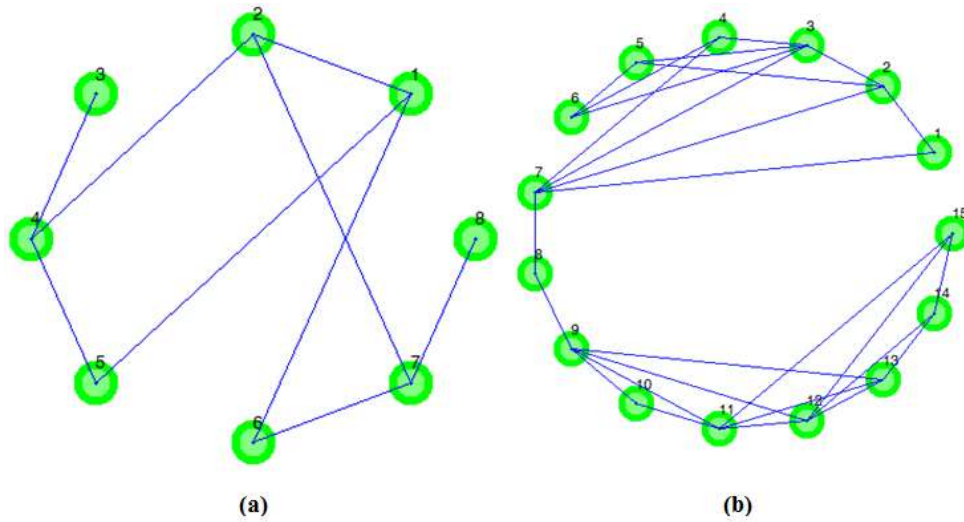
Figure 7.17 (a) FAG for dashboard of vehicle interior. (b) FAG for floor panel and center

console of vehicle interior.

The geometrical analysis of the spanning trees for both components generates the flat pattern that corresponds to each spanning tree, and then it detects any overlapping. The results of the FPA for both of the vehicle interior components are in Figure 7.17. The dimensions are in mm, while the program approximates the surfaces as collocation of triangles during geometrical analysis using polygon triangulation. Both Figure 7.18 and Figure 7.19 list examples of the generated spanning trees for the topological analysis conducted for the battery enclosure.

The dashboard has only one geometrically valid flat pattern and that is referred to the fact that the main surface in dashboard that holds the monitors is curved; hence it cannot be connected to any other surface in the same direction of curvature in the 2-D phase. The flat patterns for the vehicle's interior part are shown in Figure 7.20 and Figure 7.21.

The results of optimization metrics are listed in Table 7.11, where the dashboard component has only one flat pattern. The application of stressed-based analysis and composite material study yields optimized flat patterns number 6 and 9, respectively.
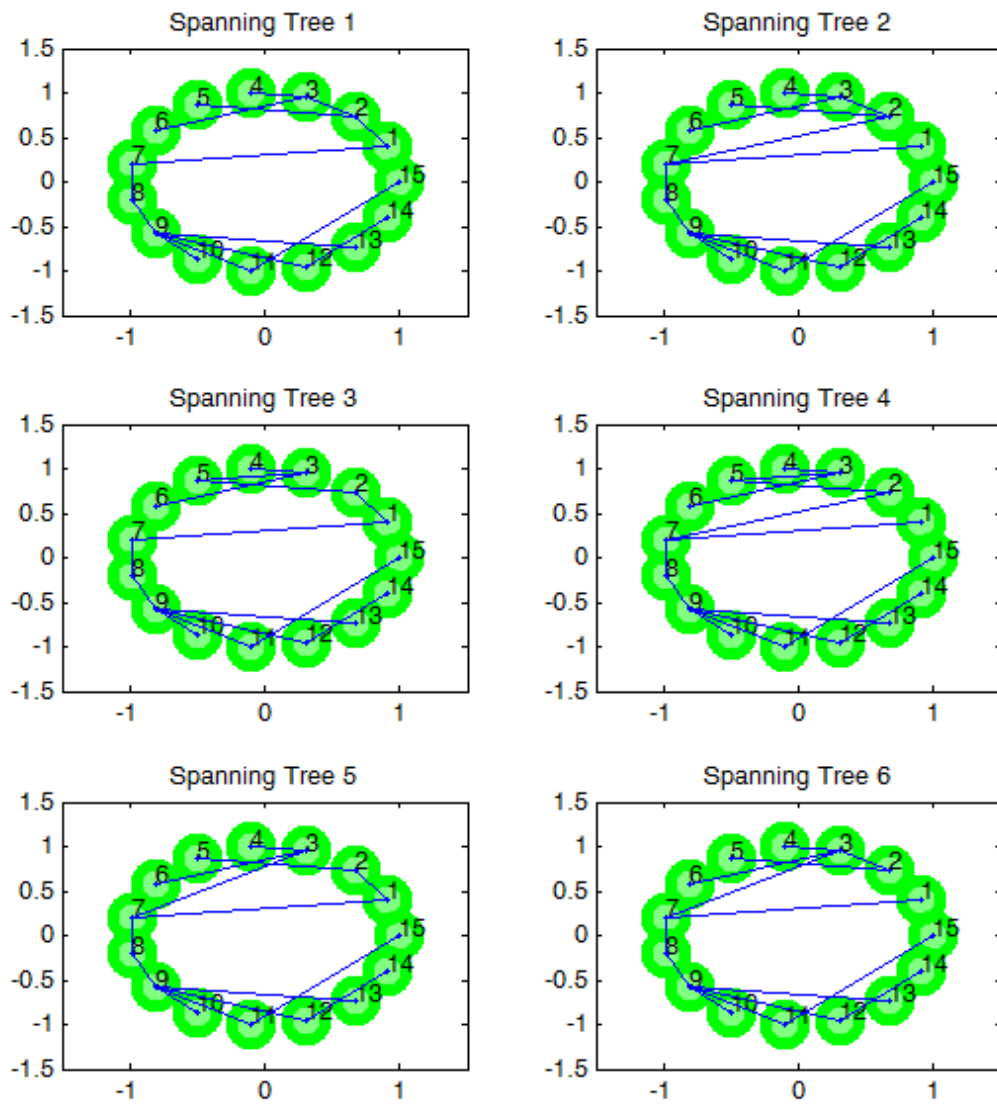
Spanning trees 1-6 for floor panel and center console

Figure 7.18 Spanning trees 1-6 for floor panel and center console.
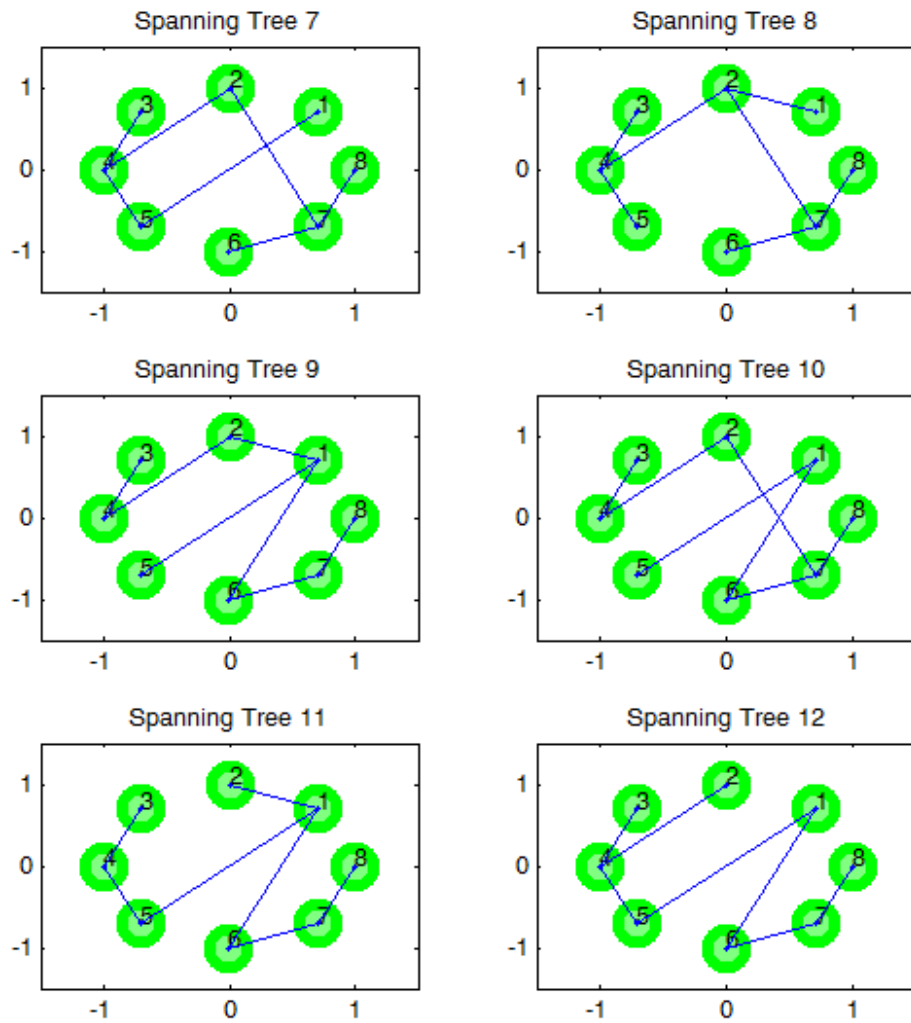
Figure 7.19 Spanning trees 7-12 for dashboard component.
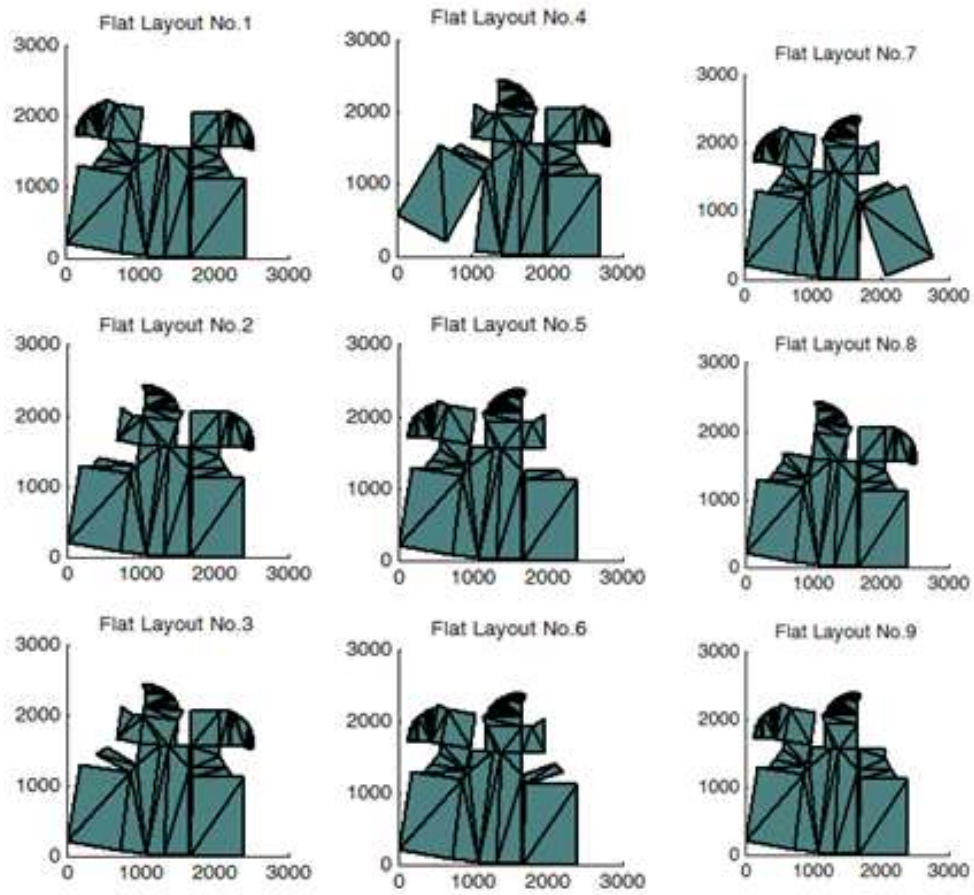
Figure 7.20 Geometrically valid flat patterns for floor panel and center console component.
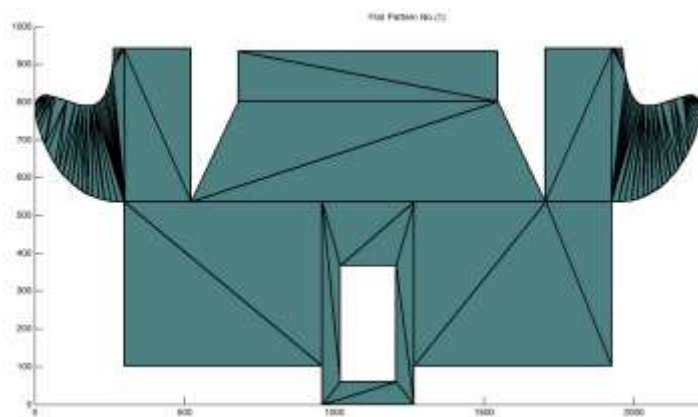
Figure 7.21 The only geometrically valid flat pattern for dashboard.

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Table 7.11 The results of optimization metrics for vehicle's Interior.

Figure	CM Geometric	CM min .OverallExtent	CM min. EnclosingArea	CM Area Condensation	NEM	NBM	OBM	WCM
7.7	Pattern 1	Pattern 1,2,5	Pattern 1,2,5	Pattern 1	Pattern 1	All equal; 7 bends	Pattern 9	Pattern 1
7.8	Pattern 1	Pattern 1	Pattern 1	Pattern 1	Pattern 1	Pattern 1	Pattern 1	Pattern 1

7.4   Floor Panel

The third part under study is the floor panel of a vehicle, Figure 7.22, however the part is not composed of a single piece of sheet metal, rather it is made of two components Figure 7.22(b)-(c).

The first component of floor panel contains 18 faces with 27 connecting edges that can lead to high number of spanning trees since the graph traversal algorithm depends on permutations of the connecting edges for the nodes in FAG, the total number of spanning trees is 97,407, however none of those spanning trees can generate a feasible flat pattern without overlapping as indicated in Table 7.12. For the second component the number of faces is less with 10 faces and 11 connecting edges, the shape can generate nine spanning trees and all of those can lead to a valid flat pattern for the component. All the generated flat patterns for the second component of floor panel are represented in Figure 7.23. All dimensions are in mm, while faces are approximated to sets of triangles by polygon triangulation to facilitate rotation and manipulation in the geometrical analysis step of FPA.
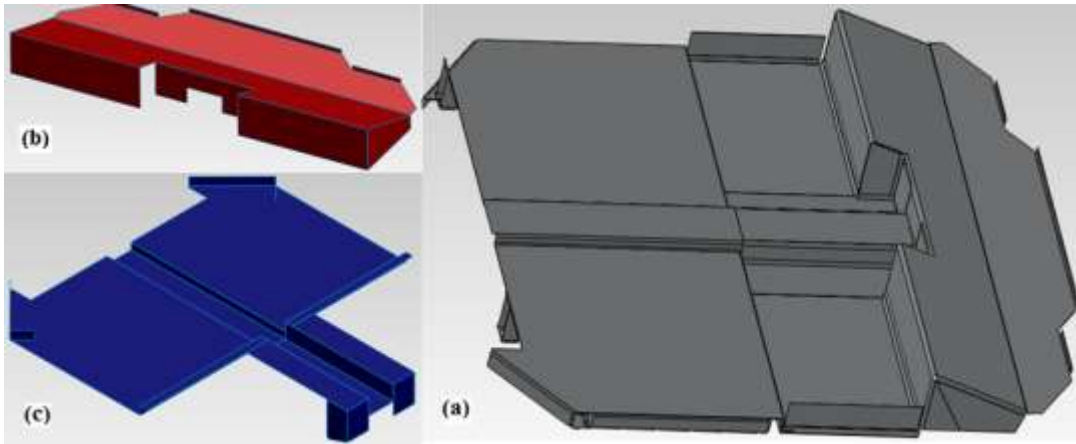
Figure 7.22 (a) Floor panel of a vehicle. (b) component-1 of floor panel.

(c) component-2 of floor panel.

Table 7.12 FPA summary results for floor panel.

Comp.	No. of Faces	No. of Edges	No. of Topologically Valid Spanning Trees	No. of Geometrically Valid Flat Patterns
Comp1	18	27	97,407	None
Comp2	10	11	9	9
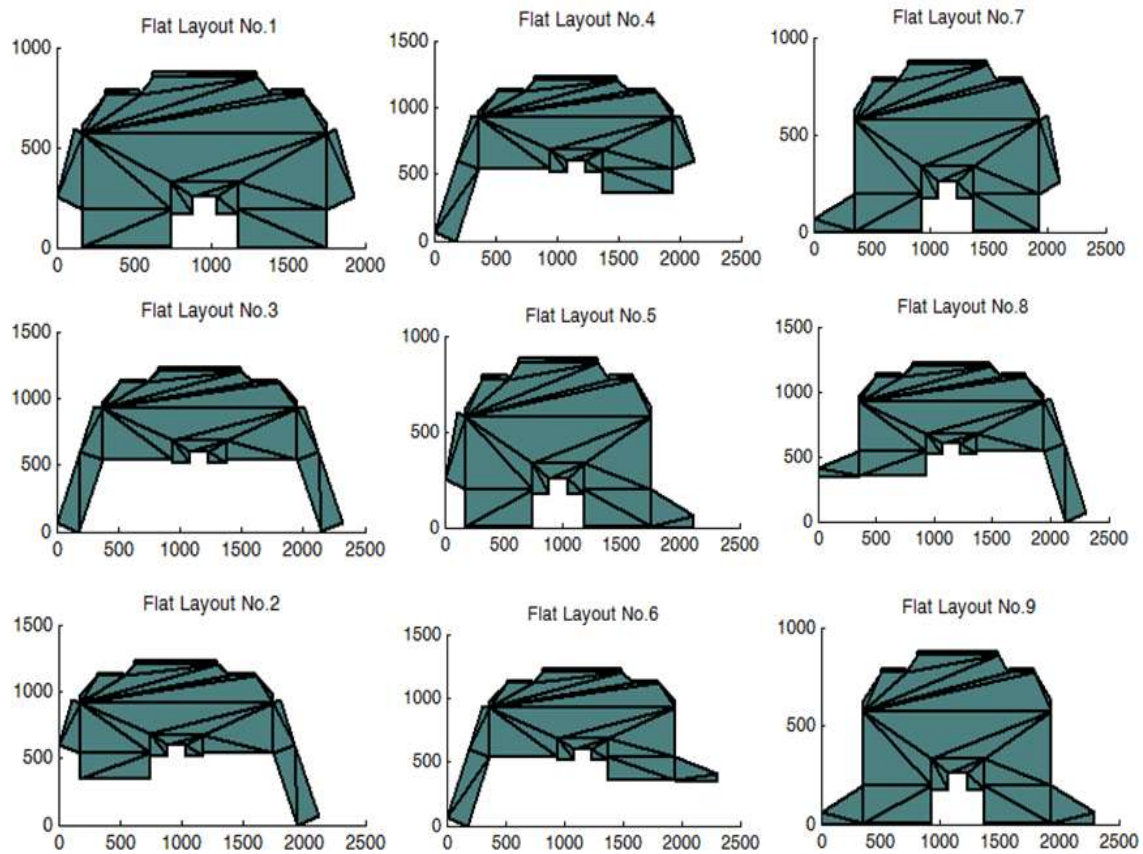
Figure 7.23 Flat patterns of component -2 of floor panel.

The results of the optimization metrics are listed in Table 7.13, where one component-1 is only considered since component-2 yielded no feasible flat pattern due to overlapping. Furthermore, the application of stressed-based analysis and composite material produced optimized flat patterns number 1 and 2, respectively.

Table 7.13 Results of optimization metrics for floor panel.

Figure	CM Geometric	CM $_{min}$ .OverallExtent	CM $_{min.}$ EnclosingArea	CM $_{Area}$ Condensation	NEM	NBM	OBM	WCM
7.22	Pattern 1	Pattern 1,5	Pattern 1	Pattern 1	Pattern 1	equal	Pattern 9	Pattern 1

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7.5   Front Module

The last part under analysis is the front module of a vehicle, the nature of the geometry of this component is different than the rest of the cases since the ratio of parts height to width is very high i.e. the front module is composed mainly of rectangular tubes where the cross sectional area is considerably small relative to the parts height. Figure 7.24 denotes the front module geometry, the front module is partially symmetrical along the longitudinal axis in terms of components except for component P0013. Moreover, the assigned number for each component is a result of bill of material and does not have any significance for FPA.

The assembly/joining method is assumed to be welding while all the fold lines are set to have material discontinuities along the bend line to facilitate the bending. The summary for resulted spanning trees and flat patterns for each of the components is listed in Table 7.14, it can be noticed that many components have large number of spanning trees, however the resulted flat patterns is relatively small due to the geometrical constraints of non-overlapping. Figure 7.25-7.30 represents the flat patterns for each of the components. All dimensions are given in mm and all faces are approximated to set of triangles.

The outcomes of the optimization metrics for the front module components are listed in Table 7.15, where component P086 has no geometrically valid flat patterns. Changes to the 3-D design of P086 component is necessary if the component to be manufactured by fold forming process.
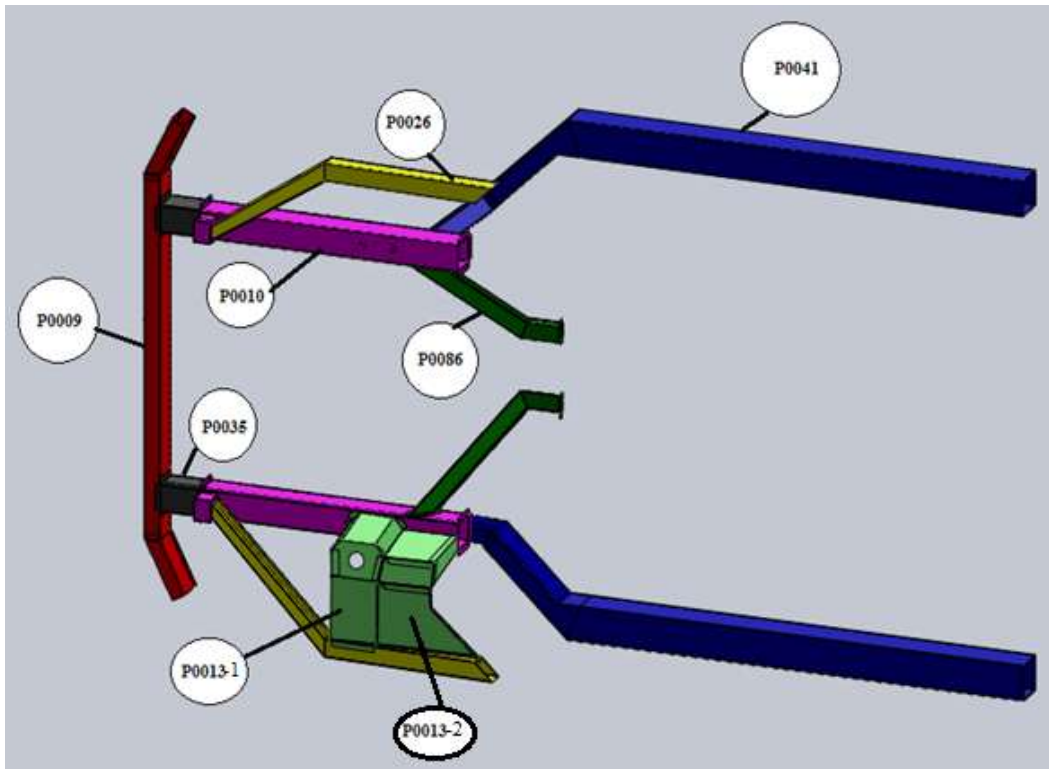
Figure 7.24 Front module of vehicle with its components.

Table 7.14 FPA summary results for front module of a vehicle.

Component	No. of Faces	No. of Edges	No. of Topologically Valid Spanning Trees	No. of Geometrically Valid Flat Patterns
P009	12	20	31500	7
P010	9	12	45	30
P013-1	15	24	663	35
P013-2	6	10	111	29
P026	8	20	384	15
P035	4	4	4	1
P041	12	20	31500	3
P086	8	12	96	None

Figure 7.25 Flat patterns of component P009 for front module.

Figure 7.26 Flat patterns of component P010 for front module.

Figure 7.27 Flat patterns of component P013-1 for front module.

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Figure 7.28 Flat patterns of component P013-2 for front module.
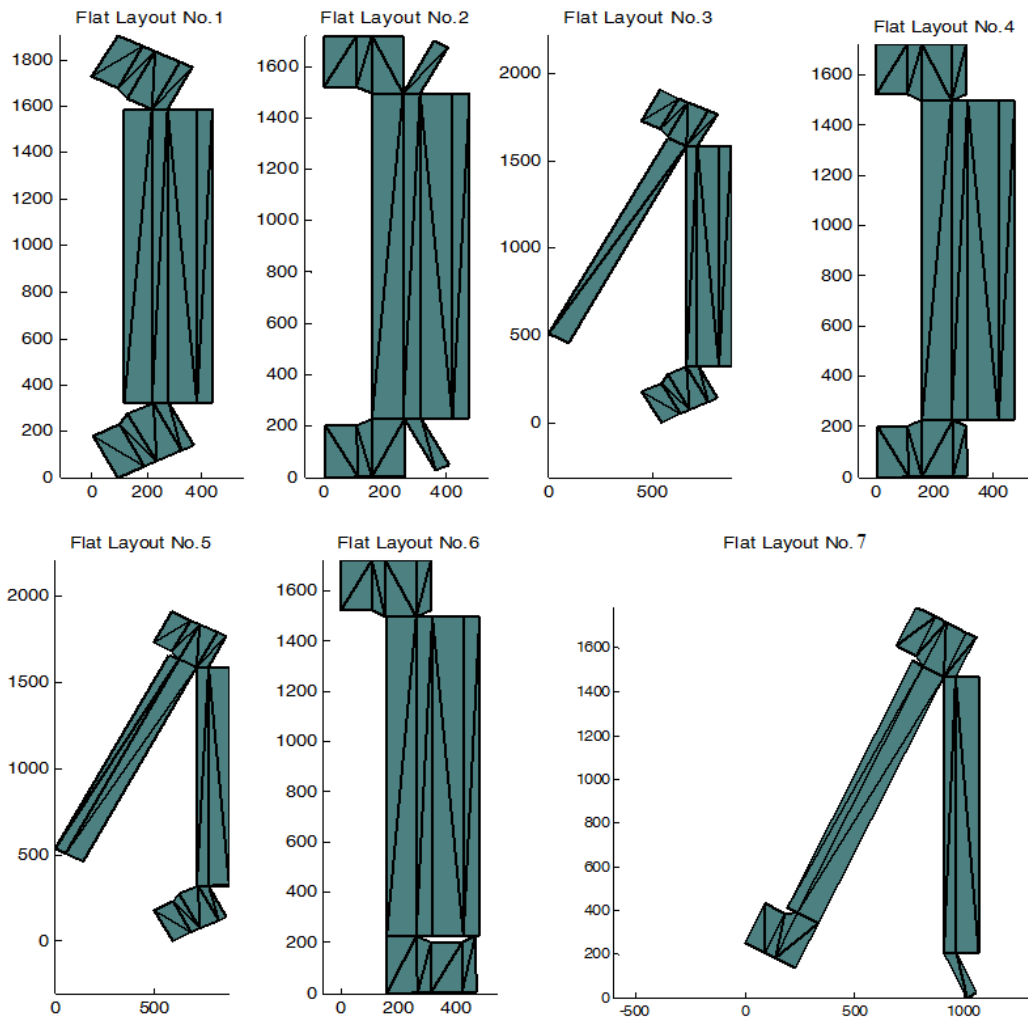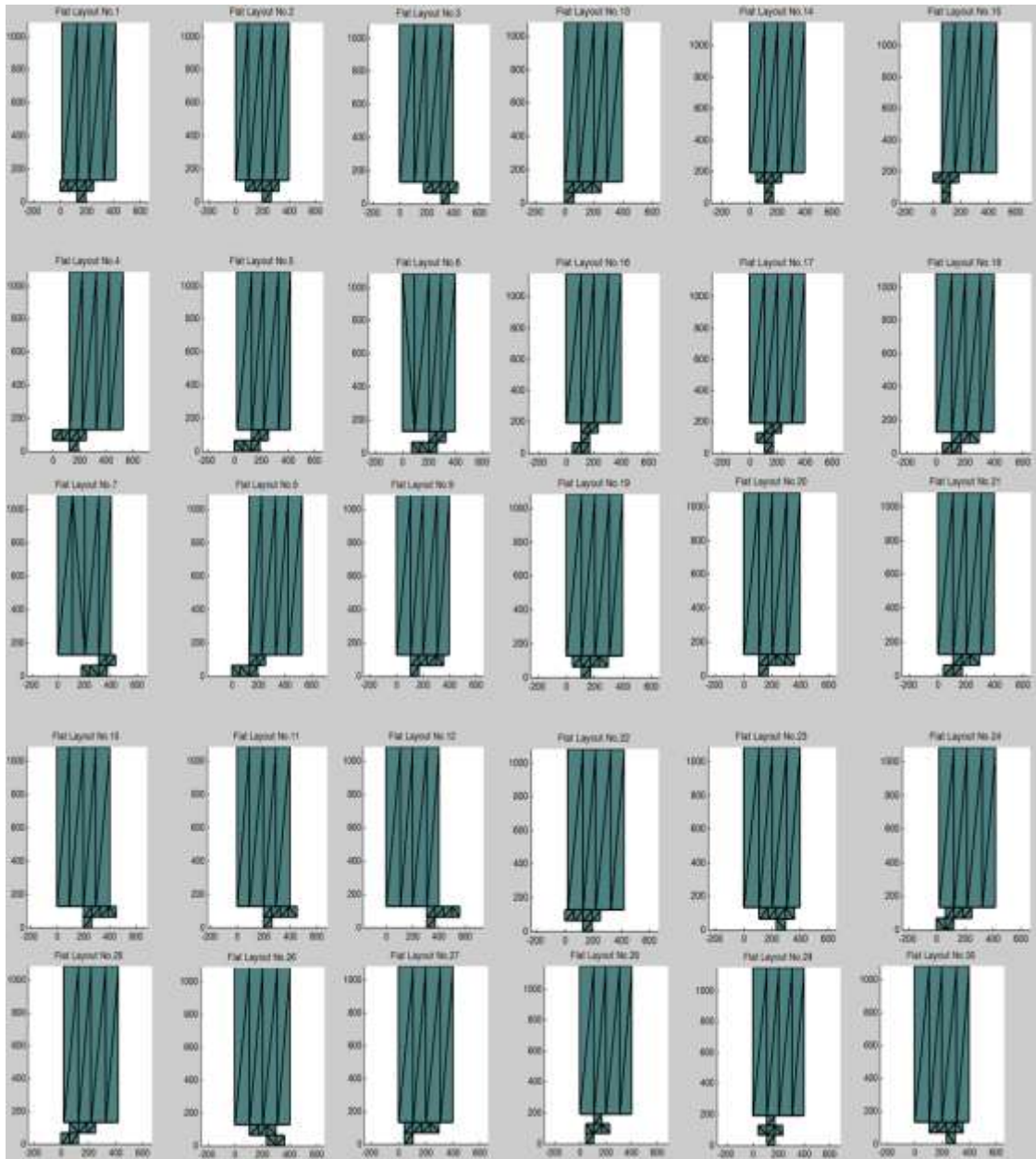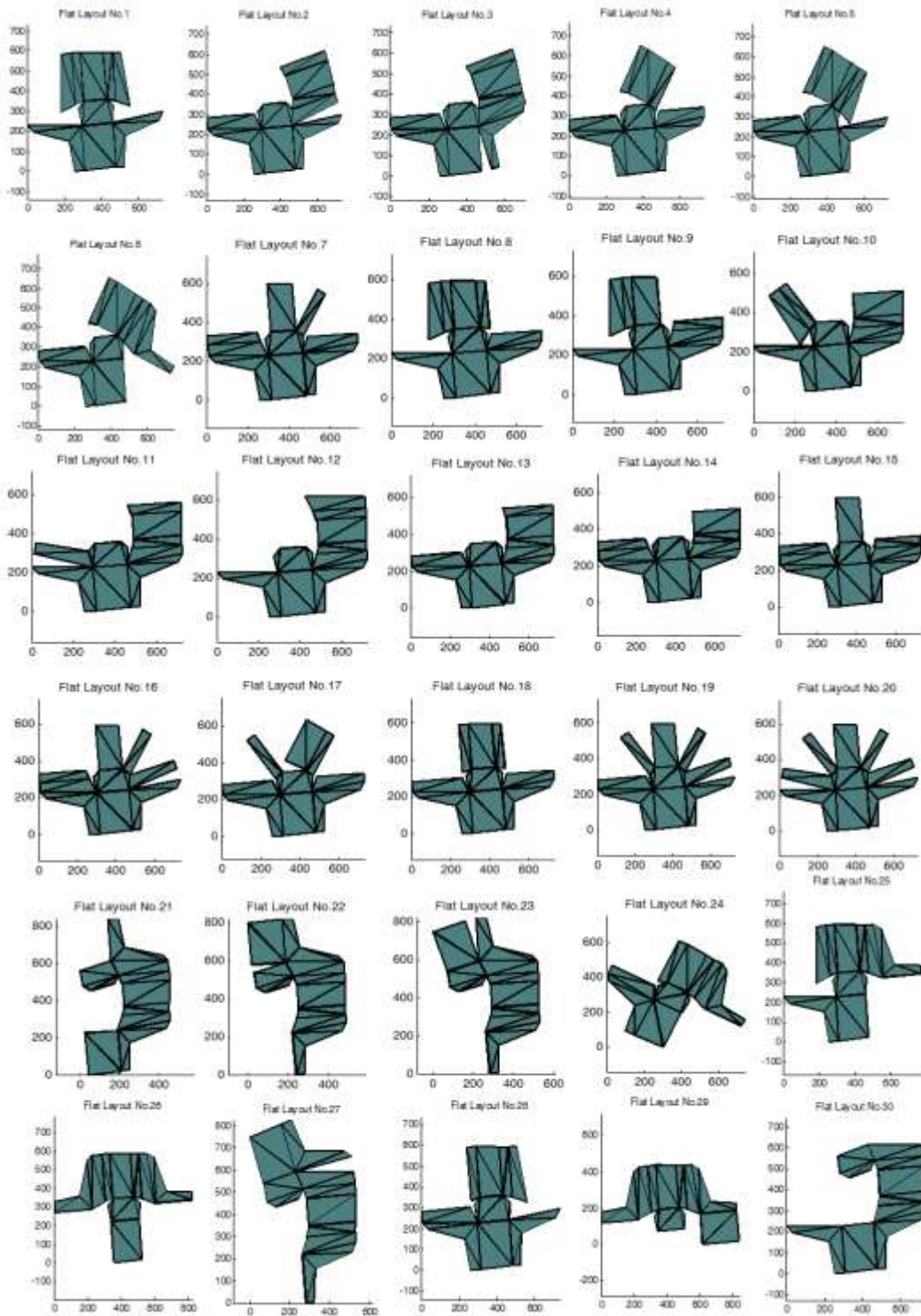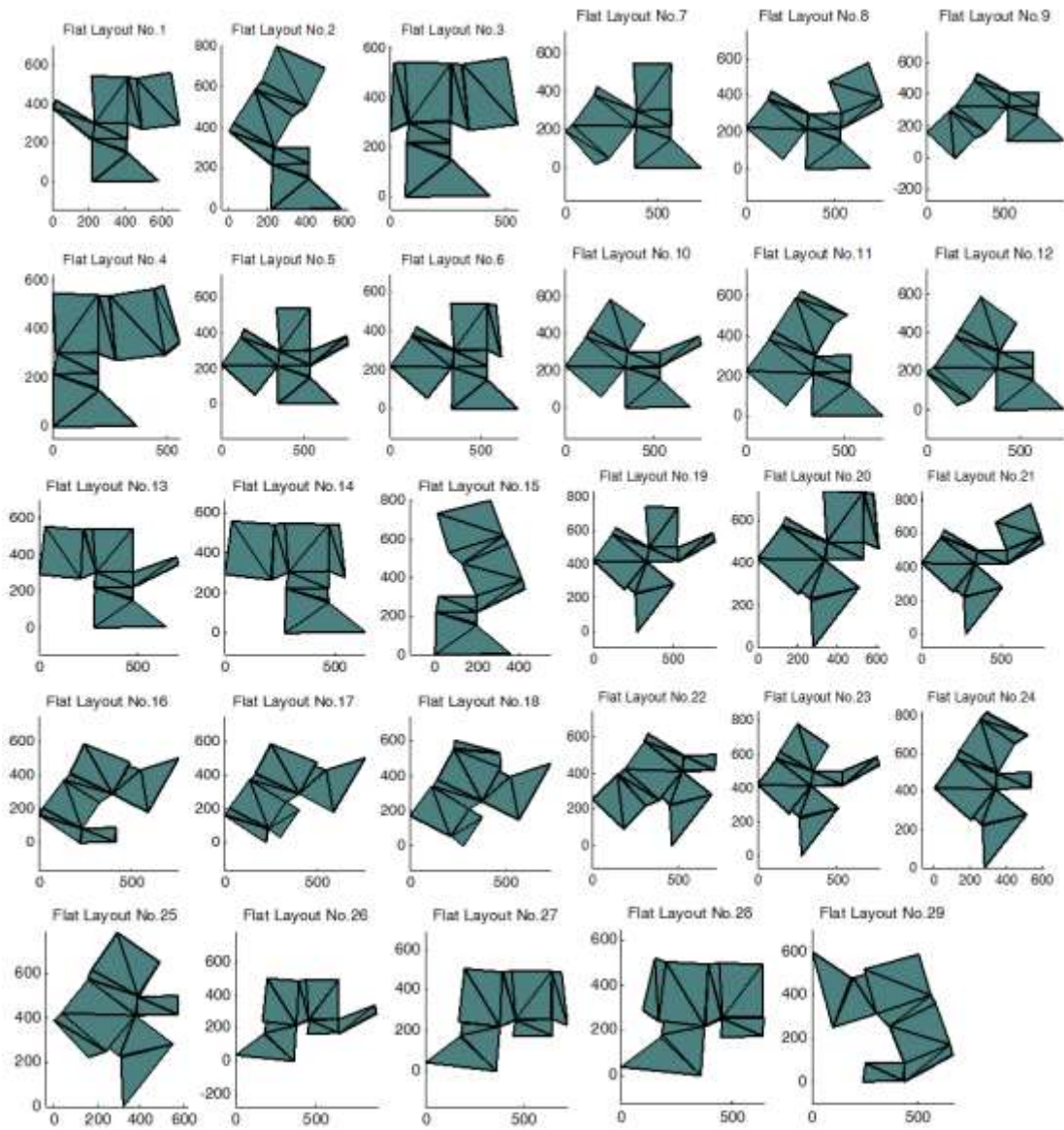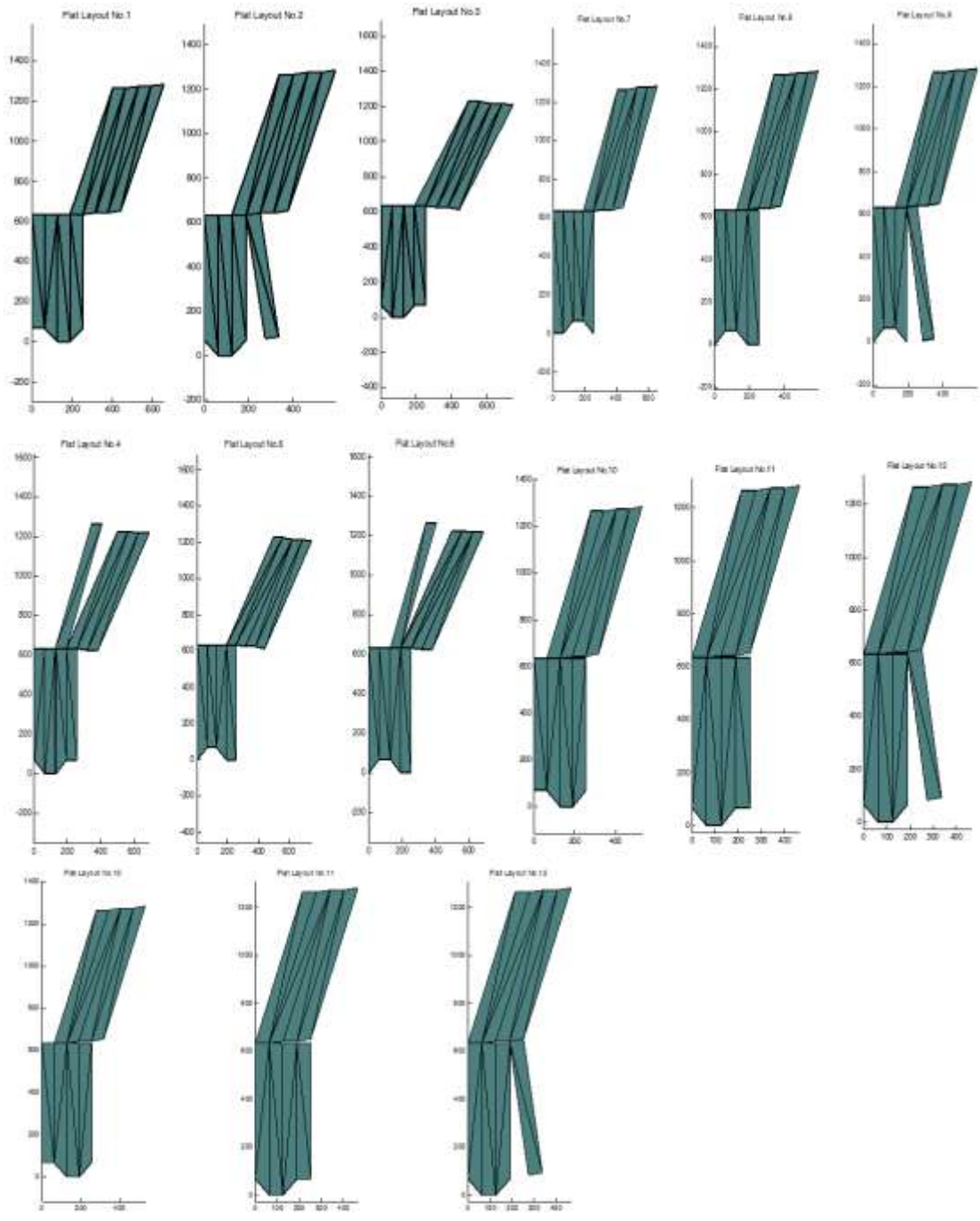
Figure 7.29 Flat patterns of component P026 for front module.
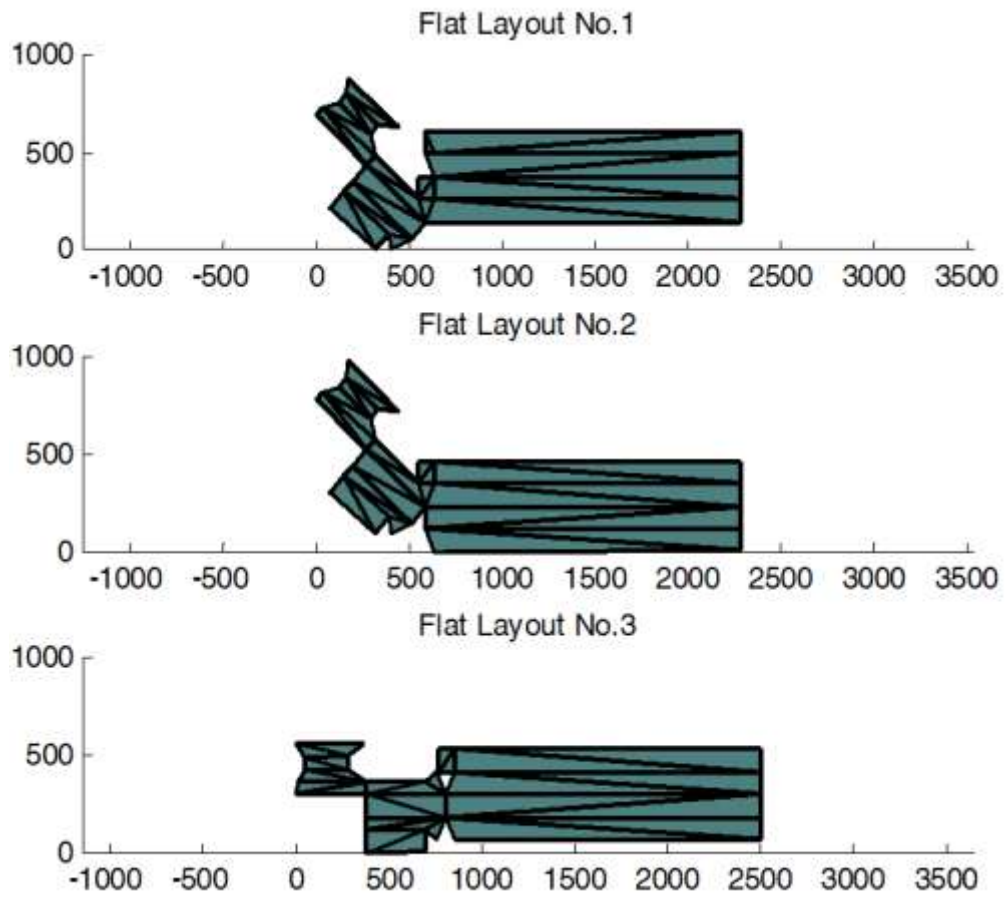
Figure 7.30 Flat patterns of component P041 for front module.

Table 7.15 Results of optimization metrics for front module.

Comp. Figure	CM Geometric	CM min. OverallExtent	CM min. EnclosingArea	CM Area Condensation	NEM	NBM	OBM	WCM
P009 7.24	Pattern 4,6	Pattern 6	Pattern 4	Pattern 4	Pattern 6	All equal; 9 bends	Pattern 4,6	Pattern 4,6
P010 7.25	Pattern 2,9,12, 18,19,2 7	Pattern 1-12, 17-22,26	Pattern 2,6,9, 12,17,18, 19,20,26	Pattern 2,6,9, 12,17,18, 19 ,20,26	Pattern 2,9,12,17, 19 ,20,26	All equal; 7 bends	Pattern 1,2,10 13,19,20, 22,23,30	All are equal
P013-1 7.26	Pattern 14	Pattern 3	Pattern 21	Pattern 21	Pattern 12, 13	All are equal	Pattern 22,23	Pattern 1
P013-2 7.27	Pattern 28,4	Pattern 3	Pattern 3	Pattern 3	Pattern 15	All are equal	Pattern 14	Pattern 3
P026 7.28	Pattern 13,10,1 1	Pattern 3,5	Pattern 11,12	Pattern 11,12	Pattern 1,11,12	All are equal; 7 bends	All are equal	Pattern 1,3,7, 8,5,10, 11
P035	Pattern 1	Pattern 1	Pattern 1	Pattern 1	Pattern 1	Pattern 1	Pattern 1	Pattern 1
P041	Pattern 2	Pattern 1,2	Pattern 3	Pattern 3	Pattern 3	All are equal	Pattern 3	All are equal
P086	None	None	None	None	None	None	None	None

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7.6 Summary

Five major components in vehicle are discussed and analyzed in this section; each folded structure is evaluated in terms of generating all possible flat patterns and applying the geometrical optimization metrics to favorably select between possible flat patterns. Moreover, stressed-based and composite material analyses are applied to evaluate the flat patterns for the battery enclosure component of an electrical vehicle.

CHAPTER EIGHT

CONCLUSIONS

8.1   Conclusions

This dissertation presented a novel scientific approach to the design of folded sheet metal products, which are fabricated by the aid of material discontinuities along the bend line. Those material features facilitate the bending and handling operations, and change the requirements of the manufacturing process and production line for fold forming. The dissertation also discussed an evaluation methodology to the fold forming process in terms of traditional production line requirements, in addition to benchmarking the fold forming process to traditional fabrication techniques used for sheet metal products.

The system initialized the examination of folded structures in terms of topological representation to investigate the transformation of 3-D folded geometry into non-overlapping 2-D flat pattern design. This representation approach enabled the application of graph theory principles and graph traversal algorithms, which explored all possible topological designs of flat patterns for a certain 3-D structure without the need of excessive geometrical manipulation. In next step, the systematic analysis utilized the boundary representation to investigate the validity of the topological results by adding the geometrical aspect to the flat pattern design. Moreover, the established approach developed optimization metrics in order to favorably select the best flat pattern design in

terms of manufacturability and cost of folded sheet metal products, those optimization metrics provided the designer with judging tools to evaluate the potentials of each flat pattern profile in early stages of the design phase. Hence, the system involved the manufacturing process needs in the product design phase.

In the following stage, the created system encountered for stressed-based performance in the design analysis. A systematic methodology was identified to determine the load bearing capabilities of the 3-D folded structure with respect to the flat pattern design used to fold it. The first established step in stressed-based analysis was the modeling of the 3-D structure as a set of nodes and elements; this technique was facilitated by the polygonal approximation for the structure's faces. The axial stress exerted on each element was determined by utilizing structural matrix analysis, where the stiffness matrix was calculated for each element. Afterward, the global stiffness matrix can be computed. This technique provided sufficient insight for the load bearing capabilities of the geometry without the need to conduct detailed finite element analysis using software packages.

The results of axial stresses indicated the critical elements which should not be assigned as fold lines because of the material discontinuities that weakened the fold line. Accordingly, modification parameters were introduced to accounts for the differences between weld and fold lines with respect to material strength. The elements that represent fold lines in the structural analysis is weakened, hence the elemental stiffness matrix is multiplied by 0.6, while the elements referring to weld line is strengthened by 1.2 factor. This strategy simulated the actual material status in terms of stressed-based performance

and lead to the optimization flat pattern in terms of resulted axial stress under defined set of forces.

Subsequently, the developed system accounts for the effect of material type in the design of folded sheet metal product. A structural analysis was established for component made of composite material, the significance of the analysis is due to material's anisotropy, which influenced the product characteristics specially when combined with the different combination of fold and weld lines in flat pattern designs. The best fiber orientation for optimized material strength was investigated using elasticity theory of composite material; the analysis defined the modulus of elasticity in terms of fiber alignment under specific global applied stresses. This result was used to determine the flat pattern design with seam lines under excessive peel shear stress; the study examined the combination of fiber alignment and the orientation of adhesively bonded edges in the produced 3-D product. The defined evaluation steps aimed at increasing the fracture load of bonded edge that is directly affected by the fiber direction. Furthermore, the study account for the total joined length of a 3-D structure design; hence an optimization algorithm is developed to define the flat pattern profile with least total bonded length.

In terms of manufacturing process analysis, the dissertation provided a KBS as an evaluation tool for the design of production line of BiW panels, the tool utilized QFD and AHP approaches to connect between customer needs and process requirements, afterwards the tool benchmark the fold forming process with respect to traditional manufacturing process. The advantage of the KBS is the ability to computerize the expertise and knowledge of engineers within the tool, hence the system is adaptive and

continuously improving as the building knowledge is increased and modified. In addition, the tool exhibited a graphical interface, which generated graphical results for better visualization and assessment purposes.

The proposed system was used to examine several automotive components made of sheet metal. The results explored all possible designs for a single part and favorably rated them according to the optimization metrics, stress-based analysis and composite material investigation.

Moreover, the main requirements of a production line for BiW panels were extracted form process attributes, and then it was reflected on the selection of a manufacturing process to cope with production requirements. The analysis indicated that reduction in number of components and the consolidation of parts are key parameters that affect the production line design for BiW panels.

8.2   Contributions

A comprehensive scientific approach was developed for folded sheet metal products and process, the system depended on rule-based evaluation for six different aspects, those are topological and geometrical requirements, manufacturability needs, minimum product and process cost, stress-based analysis, application of composite material, and process selection in terms of production requirements.

Previous analysis approaches do exist for folded products. However, they are designed for paper-based folded structures that exhibit different geometrical and stress-based characteristics. Moreover, none of the available studies expanded the analysis of folded structures beyond topological and geometrical requirements. These limitations

make them unable to handle sheet metal folded structure in terms of design and manufacturability, besides the mechanical and material performance which play a key role in engineering parts.

The followed methodology in this dissertation established scientific bases for the analysis of folded sheet metal parts and process design, the major constructed steps included a novel topological analysis approach to determine validity and possible design of 2-D flat patterns, specifically through graph modeling and graph traversal algorithm. In addition to a tool that checks the geometrical validity using B-rep modeling and overlapping detection.

The work also defined optimization metrics to account for the manufacturability and cost requirements traditionally encountered for sheet metal products as nesting efficiency, total welding cost, handling requirements during unfolded state, and bending operation complexity in terms of bend lines orientations.

Furthermore, the study introduced the stress-based performance under applied loads to analyze the design of folded sheet metal parts, the examination used structural matrix approach along with polygonal approximation to model and investigate the axial stresses exerted in each fold and weld line. This is among the first studies that included stress-based performance for folded structures and defined a systematic methodology to the analysis. Additionally, the effect of material's anisotropy, specifically composite material application, for folded structures was studied thoroughly in terms of fiber orientation, total bonded length and direction of sheer peel with respect to fiber

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alignment. This tool provided the designer with main insight on the effect of material type of folded geometries in engineering application.

Finally, the system contains a tool to evaluate the fold forming process with respect to other traditional manufacturing processes. This unique evaluation is conducted with respect to process attributes and production requirements, while utilizing QFD and AHP tools packaged into KBS. Hence, the tool retains many advantages of being an expert system where many knowledge and expertise are stored, and the ability to perform evaluation analysis using known tools (i.e. QFD and AHP), while storing the results and share them easily through graphical and web-based applications.

8.3   Limitations and Future Work

The design of flat patterns may vary with respect to the optimization criteria followed that means the system can generate one flat pattern design that is best optimized in terms of material utilization. However, the stress-based analysis can lead to a different flat pattern design to satisfy the load bearing capabilities. Hence the user needs to define priorities of flat pattern optimization to define the best suitable candidate for the application.

Moreover, the topological and geometrical analyses of the parts are heavily depended on the complexity of the 3-D folded structure. Therefore, complex components require longer processing time and memory of the system. The complexity of 3-D folded geometries can also lead to no flat pattern designs feasible for manufacturing as a result of overlapping faces. This also is demonstrated in computational geometry science by O'Rourke (1998) in Figure 8.1, where the complexity of folded components if

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demonstrated by the number of vertices, and as the number of vertices increase the probability that all flat pattern are actually overlapping approaches one. This problem cannot be predicted before conducting the analysis, since no indication can be concluded form the folded part geometry to determine its validity for the analysis.
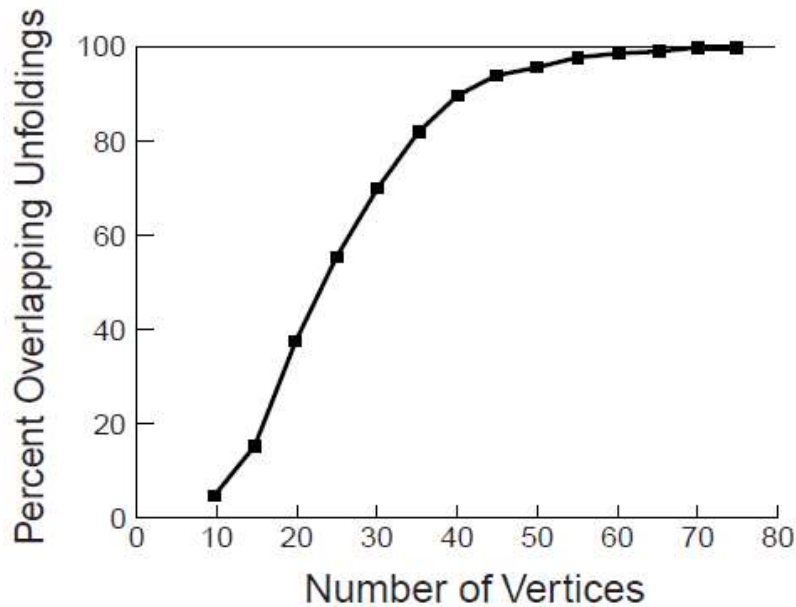

Figure 8.1 The effect of component complexity on generated flat patterns
(O'Rourke 1998).

The complexity of 3-D folded geometries can also lead to no flat pattern designs feasible for manufacturing as a result of overlapping faces. Figure 8.2 displays two dash boards designs, where one of them yields no feasible flat pattern due to overlapping.

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No valid flat pattern due to overlapping.

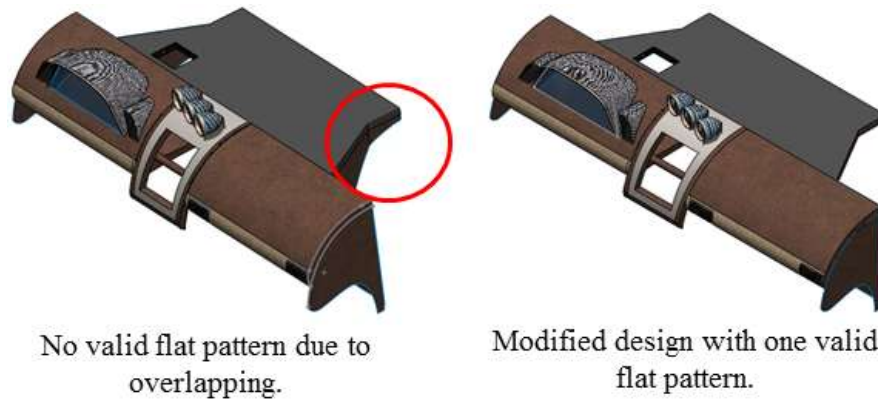Modified design with one valid flat pattern.

Figure 8.2 The effect of component complexity on final design of component.

The future work includes analysis of material discontinuities effect on the folded sheet metal parts in terms of the shape and dimension of the features. The analysis of material discontinuities effect on the folding operation requires further investigation for the accuracy, force requirements, and tendency to develop cracks and tears of folded sheet metal parts. The features vary in terms of shape, dimensions, and separating distance between features, Figure 8.3 illustrates examples of suggested features shapes and dimensions found in literature.
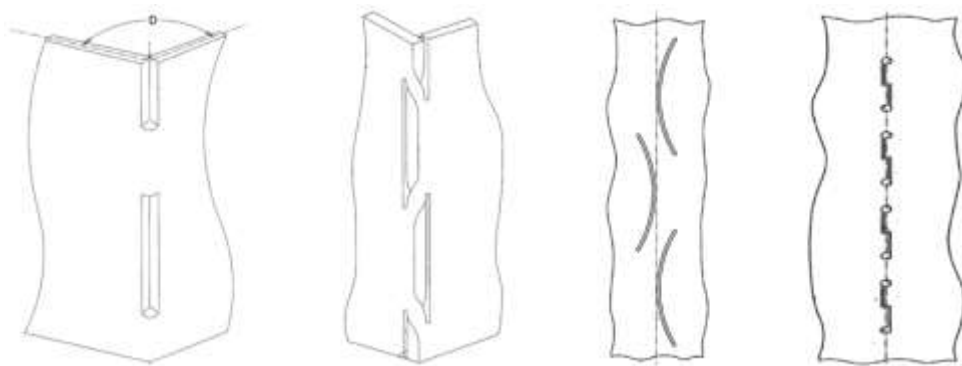

Figure 8.3 Various possible features designs for folded sheet metal products.
(Durney 2006, Gitlin et al. 2003)

Furthermore, the future work includes the influence a stamped or cut feature has on the final mechanical performance of the sheet metal part. The areas of investigation consist of the following prospective;

- The effect on localized stresses along the bend line.

- The effect on mechanical performance under loading.

- Accuracy of folding operation (resulted angle, fold line location).
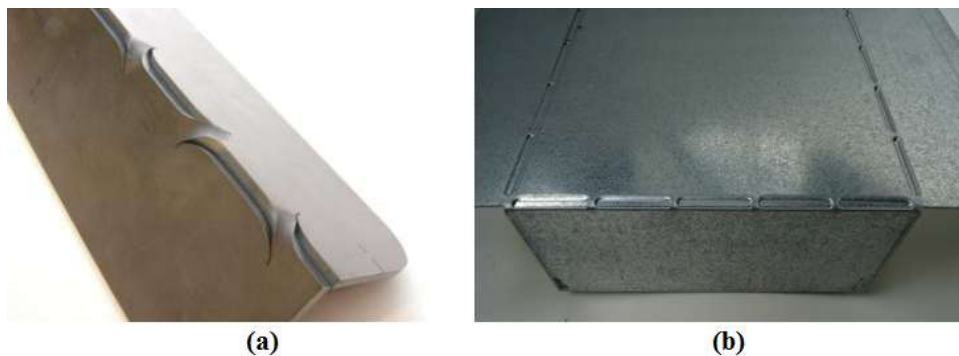
Figure 8.4 Folded sheet metal products by industrial Origami® (a) laser cut features. (b) Stamped features.

Another aspect of folded metallic structures to explore the contribution of fold forming process in terms of flexible manufacturing systems and sustainability; this can be translated into flexible sequence of processes, modularity of manufacturing cells, and changes to thermal cure step. Figure 8.5 illustrates the current process sequence for BiW panels. The major anticipated changes in operations characteristics can affect forming, storage, adhesive bonding, and thermal cure operations.

Figure 8.5 Current process sequence for BiW panels of a vehicle.

CHAPTER NINE

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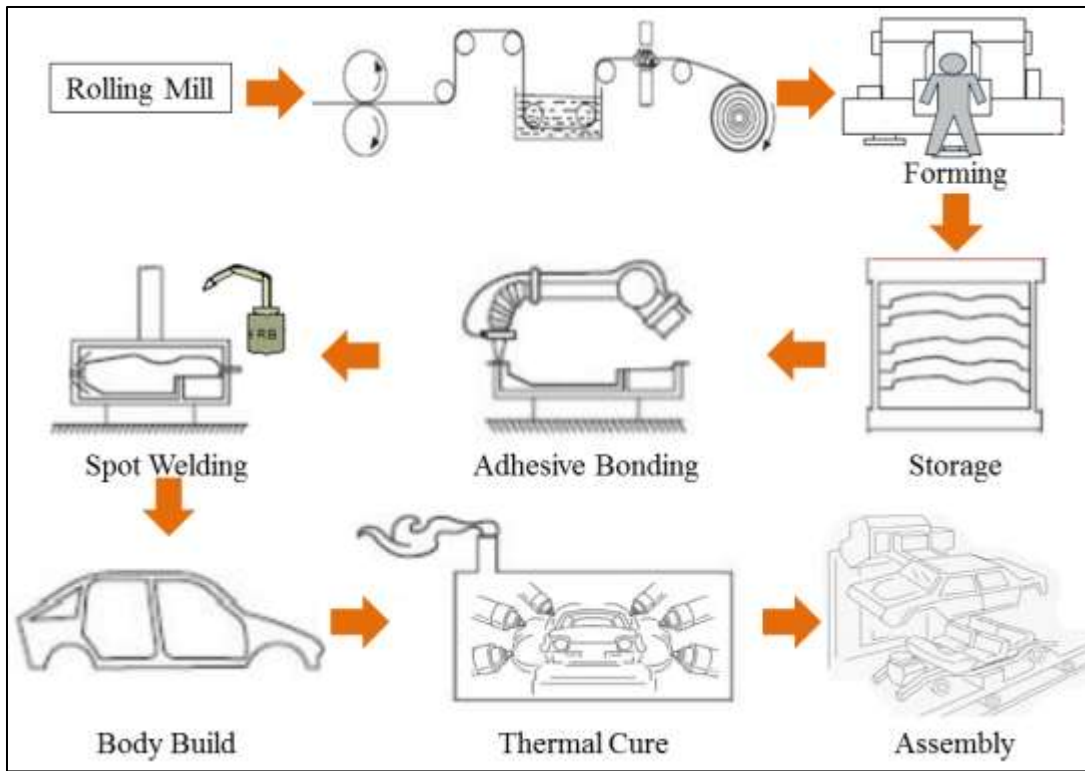Balkcom, D., Mason, M. (2004).Introducing robotic Origami folding. Proceedings of IEEE International Conference on Robotics and Automation, New Orleans, LA .pp. 3245-3250.

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