Methodology for the design of a reconfigurable guillotine shear and bending press machine (RGS&BPM)

Vennan Sibanda, Khumbulani Mpofu and John Trimble
Department of Industrial Engineering, Tshwane University of Technology, Pretoria, South Africa

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Abstract

Purpose – In manufacturing, dedicated machine tools and flexible machine tools are failing to satisfy the ever-changing manufacturing demands of short life cycles and dynamic nature of products. These machines are limited when new product designs are introduced. The solution lies in developing responsive machines that can be adjusted or be changed functionally when these change requirements arise. These machines are reconfigurable machines which are becoming the new focus, as they rapidly respond to product variety and volume changes. A sheet metal working machine known as a reconfigurable guillotine shear and bending press machine (RGS&BPM) has been developed. The purpose of this paper is to present a methodology, function-oriented design approach (FODA), which was developed for the design of the RGS&BPM.

Design/methodology/approach – The design of the machine is based on the six principles of reconfigurable manufacturing systems (RMSs), namely, modularity, scalability integrability, convertibility, diagnosability and customisability. The methodology seeks to optimise the design process of the RGS&BPM through a design of modules that make up the machine, enable its conversion and reconfiguration. The FODA is focussed on function identification to select the operational function required. Two main functions are recognised for the machine, these being cutting and bending; hence, the design revolves around these two and reconfigurability.

Findings – The developed design methodology was tested in the design of a prototype for the reconfigurable guillotine shear and bending press machine. The prototype is currently being manufactured and will be subjected to functional tests once completed. This paper is being presented not only to present the methodology by to show and highlight its practical applicability, as the prototype manufacturers have been enthusiastic about this new approach.

Research limitations/implications – The research was limited to the design methodology for the RGS&BPM, the machine which has been designed to completion using this methodology, with prototype being manufactured.

Practical implications – This study presents critical steps and considerations in the development of reconfigurable machines. The main thrust being to explore the best possibility of developing the machines

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with dual functionality that will assist in availing the technology to manufacturer. As the machine has been development, the success of the design can be directly attributed to the FODA methodology, among other contributing factors. It also highlights the significance of the principles of RMS in reconfigurable machine design.

Social implications – The RGS&BM machine is an answer for the small-to-medium enterprises (SMEs), as the machine replaces two machines with one, and the methodology ensures its affordable design. It contributes immensely to the machine availability by eliminating trial and error approaches.

Originality/value – This study presents a new approach to the design of reconfigurable dual machines using principles of RMS. As the targeted market is the SME, it is not limited to that as any entrepreneur may use the machine to their advantage. The design methodology presented contributes to the body of knowledge in dual reconfigurable machine tool design.

Keywords Reconfigurable manufacturing system, Reconfigurable machines, Methodology, Reconfigurable guillotine shear and bending press machine, Function, Metal sheet

Paper type Research paper

1. Introduction

It has been noted in modern production systems that product life cycles are decreasing while the number of product variations keep increasing (Bortolini *et al.*, 2018). With such an increase in the frequency of new products, Andersen *et al.* (2015) advocated for a matching manufacturing system, the reconfigurable manufacturing system (RMS) that would rapidly change cost effectively to meet different product demand conditions in terms of variation in volume and characteristics. The RMS was developed by taking advantages of high production volumes in dedicated manufacturing lines (DMLs) and flexibility of flexible manufacturing systems (FMS) with a specific aim of enhancing the responsiveness of the manufacturing system to any changes in product demand (Koren, Gu and Gu, 2018). A comparison of the systems is highlighted in Figure 1.

In sheet metal manufacturing, sheet metal products find applications in both industrial and consumer goods. Products such as motor vehicle bodies, freezers, computers, stoves, trolleys, heavy plant and equipment, hospital equipment, aerospace applications and many more are produced from sheet metal as either frame, housing or other designs.

Manufacturing of sheet metal products borders on the use of two machines, a guillotine shear and a bending press, effectively meaning two machines are required to process one part. For cutting sheets of large cross sections, especially long sheets, heavy-duty guillotine shears are used while for bending sheets for parts that require long lengths, tandem-bending presses are used. The impact of this is a costly investment in machinery that may not be fully used on a continuous basis. This is one fundamental that clearly demonstrates the need for reconfigurable machines. Sheet metal processing has gained an increased popularity, as it exhibits environmentally friendly operations with minimum waste (Ingarao *et al.*, 2011). To reduce investment and production cost of sheet metal products, it is imperative that a dual reconfigurable machine be developed. According to Singh *et al.* (2019), reconfigurable

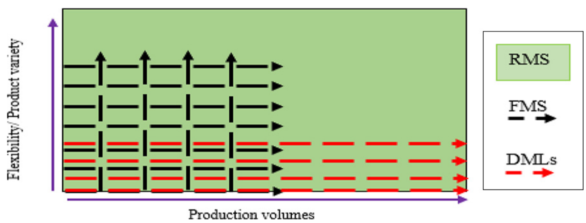


Figure 1. Comparison of manufacturing systems in capacity and product variability

machines have been available for milling, turning and drilling and now they are found as a reconfigurable assembly fixture (RAF); reconfigurable bending presses; reconfigurable inspection machines (RIMs); and the reconfigurable vibrating screen (RVS), among others (Sibanda *et al.*, 2019). Other researchers developed other reconfigurable systems for industrial applications. Fuzzy logic was used for multi-level decision-making in RMSs (Mpofu and Tlale, 2012); a generic modular reconfigurable platform for a product-oriented micro manufacturing system was designed by (Sun and Cheng, 2008). The development of a reconfigurable bending press (RBPM) by Gwangwava (2014), laid a foundation stone for the development of reconfigurable sheet metal machines. Riding on that design, a reconfigurable guillotine shear and bending press machine (RGS&BPM) with dual functionality was designed. However, it is prudent to note that no research has focussed on a reconfigurable machine with dual functionality like the RGS&BPM. This paper presents a methodology for the design and reconfiguration of RGS&BPMs. Critical sections of the methodology that look at the evaluation of the machine structures such as deformation and stiffness analysis are taken as the basic fundamental to already existing methods of machine design and evaluation synthesis. The design methodology, the function-oriented design approach (FODA), is premised on initial function identification with subsequent identification of modules that support the identified function and then classifying the modules for easy identification. Sheet metal working, cutting and bending, will be briefly introduced in the following sections and then a detailed FODA methodology description will be presented. This paper gives an overview of sheet metal forming processes, the machines used and technological advances, including process planning and how it relates to the design of RGS&BPM. It then gives a detailed FODA methodology for the RGS&BPM design based on satisfying all the six principles of RMS.

2. Reconfigurable manufacturing systems

RMS was defined by Koren (1999), as “a system designed at the outset for rapid change in structure, as well as in hardware and software components, to quickly adjust production capacity and functionality within a part family in response to sudden changes in market or in regulatory requirements”. According to Ashraf and Hasan (2015), the RMS is designed to satisfy the requirements of a product family by instituting changes in its modular hardware and software components rapidly responding to fluctuations in the market demands. To institute the changes, the RMS is designed around six principles, which are, modularity, scalability, integrability, convertibility, diagnosability and customisation. Their importance lies in that they reduce time and cost of reconfiguration, resulting in the enhancement of the responsiveness of the system. Table 1 demonstrates the importance of these principles.

RMS cannot function without two main components, the reconfigurable machine tool (RMT) and the reconfigurable controller (Krishna and Jayswal, 2012). The reconfigurable structure of RMTs provides a platform for customised flexibility with a variety of substitute features (Touzout and Benyoucef, 2019). Reconfiguration provides the means for the machine tool to respond to various changes in the product or family of parts to be manufactured (Kar and Singh, 2015). RMSs are spreading throughout the manufacturing spectrum, having been in milling, turning, drilling, inspection, etc., they are now setting route in sheet metal forming areas.

3. Sheet metal forming processes

Sheet-metal forming can be classified into two broad categories, stamping and fabricating (Altan and Tekkaya, 2012). Stamping consists of shearing or cutting operations such as blanking, punching, slotting, notching, slitting, etc., and non-cutting operations such as

Principle	Application	Interpretation
Modularity	Components are modular, such as: Structural elements, axes, controls, software and tooling	Creation of detachable self-contained unit structures of components for the system that are added, replaced or upgraded to suit new applications. Compartmentalisation and classification of changeability enablers (modules) into units that can be manipulated among alternate production structures for optimal arrangements in changing functional capacity
Scalability	Capacity change enablers. (Designed for capacity change)	Addition or subtraction of modules to change the production capacity of the system Modifying the production capacity by adding or removing modules and changing the system components to scale up or down the production system capacity
Integrability	Rapid system integration methodologies/interfaces (Interfaces for rapid integration)	Enable rapid and precise integration of modules through control and communication systems The integral connection and linking of modules to rapidly and precisely integrate modules through mechanical, information and control interfaces
Convertibility	Designed for functionality changes (at the machine level and at a higher level)	At the machine level, the machine switches from producing one-part family to another. At higher level, adding functions, extending the size of the tool magazine or expanding the range of the system functionality to produce new parts. System/machine ability to easily transform or change existing functionality to suit new production and market requirements
Diagnosability	Designed for diagnostics. Detection of machine failures and identifying causes for changes in part quality	After reconfiguring the system, it must produce quality parts as per requirements. Any deviations should be identified and corrective action taken. Control technologies, statistics and signal processing techniques are used
Customisability	Flexibility limited to part family	Enables the production of a family of parts, or product family no single parts. Customised flexibility is possible through dominant features in part families. It takes advantage of group technology

Source: Adapted from: Koren *et al.*, 2018

Table 1.
Principles of RMS

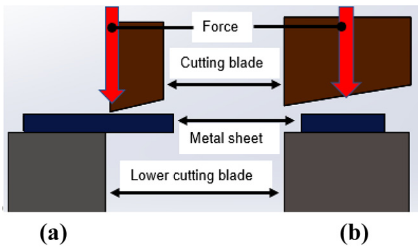
bending, drawing, stretch forming, embossing, spinning and many others. Cutting or shearing is used to generate blanks that are further worked to create various end products for either domestic or industrial applications. This is achieved through a guillotine shearing machine or laser cutter. When using a laser cuter, operations such a punching, slitting, notching are eliminated as the machine has the capability of producing these shapes as it generates the blank. After a blank has been created it is then fed to a bending press to produce the required bend features. This paper, therefore, focusses on these two machines, the guillotine and bending press which have been designed into a single hybrid machine with dual functionality.

3.1 Guillotine shear machines

Sheet-metal forming operations begin from creating a blank of suitable dimensions for a required part. The machine bed is the worktable on which the operator introduces the metal sheet. It also supports the lower shearing blade (MomohBello *et al.*, 2014). For accuracy in cutting, a squaring arm is used to adjust the sheet so that it lies square to the blades. In some machines, it incorporates a measuring scale to measure short parts from the machine instead of using gauge bars or stoppers (Altan and Tekkaya, 2012). Work holding devices stabilise the sheet by restricting it from squirming or moving while shearing is in progress. The sheet obtained from a large sheet (usually coiled) is subjected to shear stresses, using cutting blades or knives held at an angle to each other on the machine (Kalpakjian and Schmid, 2013). Shearing is a mechanical process for cutting sheet metal into smaller cross sections using cutting blades, knives, or dies (Altan and Tekkaya, 2012). Figure 2 shows the operation of a guillotine shear and an illustration of the inclined blade. The cutting action is achieved in different types of machines through mechanical, hydraulic or pneumatic power drive systems. In hydraulic drive systems, the blade is driven in a straight down and up motion by the action of the hydraulic cylinders attached to the top ram (Shear Fundamentals, 2019).The lower blade is fixed to the machine table and the upper blade is mounted at an angle on the top ram assembly (Atkins, 2009). Cutting action is achieved by the motion of the top blade as it moves down. Blades are mounted on the top ram and lower fixed machine bed, separated by a small gap of about 10% of sheet thickness (Juneja, 2003). Four major categories exist for guillotines, these being the flat blade, the inclined blade, multi-purpose shearing machine and special shears. The flat blade machine has the two blades positioned parallel to each other, resulting in intense energy requirements for shearing. The machine is very robust with minimal deflection and mostly used in hot shearing.

The inclined blade machine has the upper and lower blades positioned to form an angle. The angle is created by the upper blade which inclines at angles varying from 1° to 6°. Because of the inclined blade arrangement, the cutting action is progressive from one end to the other, resulting in smaller shearing force requirements, hence the machine power, energy and weight are much less compared to the flat blade option (Christoforou *et al.*, 2013). There are two variations of this machine, the guillotine shearing machine and pendulum sheet shearing machine, depending on the motion of the tool holder. If classified according to the main drive system, it can be divided into two types, mechanical transmission and hydraulic transmission shearing machine.

Another variation of the guillotine shear is the multi-purpose machine which uses changeability enablers to institute both bending and cutting operations. Applications of such machines are found in Inverted Box Rib (IBR) sheets production. The final machine is the special purpose which is used in sheet coil straightening lines. For thick sheet shearing lines, there is a hydraulic high-speed shearing machine (Qin *et al.*, 2010).



Source: (Adapted: Groover, 2016)

Figure 2.
(a) Shearing side view and (b) Shearing front view upper cutting blade

For guillotine shears, a measuring or gauging system is used. Mounted at the rear of the machine, some gauges are manual while others are computer controlled. Two screw-driven bars have mounted on them a gauge plate on which the sheet is pushed until it is stopped by the plate (Kamashian, 2017). That determines the size of the sheet to be cut.

All guillotines available today are dedicated machines with permanently attached hydraulic cylinders and a fixed superstructure. Research on reconfigurable guillotines is still missing, and there is no literature on the existence of such machines. Reconfigurability seeks to improve the responsiveness of the machine in line with changing product characteristics.

3.2 Bending presses

A bending press or press brake is a machine tool used for bending metal sheets and plates into desired profiles or features (Press Brake Ultimate Guide, 2019). The sheet is sandwiched between a set of matching punches and dies forcing it to take the shape of the two. Like guillotine shears, conventional bending presses have two fixed hydraulic cylinders that drive the top ram. The top ram houses the punch holders and punches while the bottom ram holds the fixed die holders and dies. The primary characteristics of a press brake are the tonnage, working length, working height, back gauge length and stroke (Gwangwava *et al.*, 2014). Bending presses are classified according to the power source, namely, hydraulic press brake, pneumatic press brake, mechanical press brake and servo press brake (Press Brake Ultimate Guide, 2019). Hydraulic presses use hydraulic oil as their source of power, pneumatic presses use air pressure as their source of power, while mechanical presses use a crank mechanism powered by a flywheel to drive the ram vertically. An electric motor provides the initial motion to the flywheel which then uses a clutch to engage the flywheel to the crank mechanism that moves the ram vertically. A mechanical servo press uses mechanical servo-drive technology and offers the flexibility of hydraulic presses such as slide motion of the ram, speed and position control, pressing force at any slide position, speed and reliability of mechanical presses (Osakada *et al.*, 2011). All movements are achieved through the servomotor.

Modern press brakes are equipped with optical sensors which feed live data real time to enable adjustment of process parameters during bending cycles and multiple-axis computer-controlled back gauges (Gwangwava *et al.*, 2014).

3.2.1 Developments in bending press machines. The current focus on press brakes is safety and minimal manual intervention as was with their predecessors. Computer numeral control (CNC), for the machine control, makes them sophisticated machines, designed to keep pace with today's rapid changing fabricating environment, instead of limit switches that were used to control the machine moving members (LeTang, 2017). These systems enable automatic bending and, in some instances, use of robots to feed plates is used to accelerate production. One of the upgrades in press brakes is the repeatable press brake function which enables the machine to review the material databanks to automate press brake operation and reduce the amount of manual calculation required. Marschallfeld (2004) noted that software innovation leads to the ability of the software to adapt to material behaviour in real time using internal sensing and external laser sensing, the software can account for material variations including crowning and deflection. Advances in software innovation have led to improved system integration and control capabilities and hence the ability to allow the optimal and reliable transformations of motions, power, data and modules over predefined periods (Gadalla and Xue, 2017). For instance, Data M offers a device for press-brakes controlling bending angles via laser – COPRA® Laser Check. Other important features found in most press brakes today are automatic tool changers (ATC-G6) and an automatic gripper changer system (LeTang, 2017). These have an advantage while tool changing is happening the operator would be doing other tasks hence reducing the cycle time.

3.3 Sheet metal process planning

Process planning for sheet metal cutting and bending involves developing process plans for the two functional operations. A part consists of features and each feature describes the number of operations to be processed (Touzout and Benyoucef, 2019). The purpose of developing a process plan according to Touzout and Benyoucef (2018), is to define a sequencing of operations for a given RMS design (a combination machines, configurations and tools). For cutting, part decomposition is carried out to have a clear view of the part size. For designers it is critical to decompose the product into functioning parts during the product design stage to determine the geometric configuration of the parts (Wang, 2011). A three-dimensional sheet metal part, composed of bend lines and flanges, must be unfolded into a flat pattern which signifies the original blank. Decomposition also develops a process plan or strip layout that provides a clear visual representation of the sequence of operations to be used to form a part (Poli, 2001). However, as drawings are available for each part, that information is used to develop and classify the parts according to similarities, hence develop families for them. These families are then used to develop the process plans. There are two options that are may be used for process planning, it may be done manually or using a computer-aided process planning (CAPP) systems (ElMaraghy *et al.*, 2013).

According to ElMaraghy *et al.* (2013), automated process planning depends on the degree of automation and includes:

- retrieval/variant process planning, which capitalises on families of parts and revises existing master plans;
- semi-generative process planning that is created from retrieved "Master Process Plans" to develop "variant-specific" changes, however, optimising operations to be performed and their parameters using algorithmic procedures assisted by CAD models, databases, decision tables or trees, heuristics and knowledge rules; and
- generative process planning that aims to generate an optimised process plan from scratch.

CAPP is available for bending operations; however, for sheet metal cutting operations, it is available in laser cutting processes where part geometric features are critical when creating blanks for finishing on the bending press. In guillotine shears, however, the processes are generally manual although CNC guillotine shears exist, however. Currently, research is in progress on feature recognition capability to aid in CAPP systems. Literature shows that some SOLID works programs have that capability of feature recognition although the requirement is to first draw the part and then the program will automatically recognise the features. The design of the RGS&BPM does not include the development of a new CAPP system but focusses on reconfigurability through a modular structured approach. CAPP applications and use of smart technologies such as the internet of things (IoT) in the production space, augmented by the era of Industry 4.0, where cyber-physical systems (CPS), are systems that provide intensive connection with the surrounding physical world and its on-going processes and simultaneously provide and use data-accessing and data-processing services available on the internet (Monostori *et al.*, 2016). Capabilities of cyber-physical systems enable future products and systems to be transformed into more intelligent and resilient products in the changing environment (Kao *et al.*, 2015). Advances in research continue to improve CAPP systems with focus on developing an automatic computer-aided process planning (ACAPP) system that will enable the availability of an easy and automatic complete product information (Al-wswasi *et al.*, 2018). The success of ACAPP systems rests in development of automatic feature recognition (AFR) techniques for the parts. These systems, however, fall outside the scope of this article and will not be pursued.

4. Methodology for the design and reconfiguration of the RGS&BPM

Badke-Schaub and Voute (2018) argued that currently there is no common definition of design methodology; however, it details design processes and activities that should be done to achieve a certain output in the form of a product. According to Sianipar *et al.* (2013), design is a close relationship between appropriate technology (AT) and community empowerment ideas, which are then consolidated to develop a strong basic approach of a new methodology. Previous design methodologies were developed based on pure Engineering Problem Solving (EPS) approaches; however, this study delivers a fresh and comprehensive methodology that covers reconfiguration principles. Current trends look at better results of modularisation and to allow for modification of components or to design new components before starting the modularisation process (Krause *et al.*, 2017). The methodology focuses on modular design for light weight and dynamic design of lightweight product families.

4.1 Design and reconfiguration

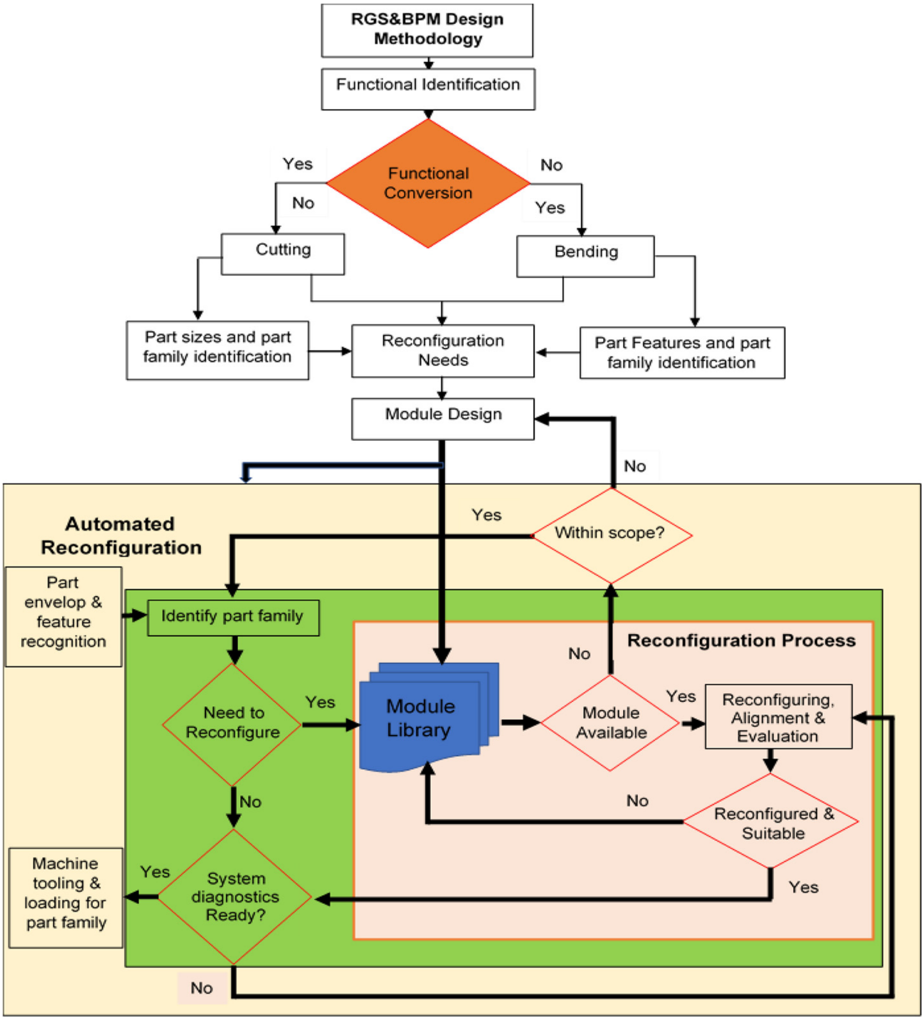
The RGS&BPM is designed to give optimum results in both functions and achieving full reconfigurability in both states. Considering that chances are very high for deflection of structural members during operation, the design focus was based on the greatest load/force that could be handled by the machine. To minimise unwarranted, dangerous defection and bending, the greatest force was calculated to be produced during the cutting process, hence the machine structural members were designed based on the greatest cutting force. Simulation analysis was carried out to compare with calculated results and indeed the machine works within safe design parameters. The machine was designed in modular fashion to enable reconfigurability.

The operational efficiency of the modular systems is supported by software that drives and controls the various applications of the conversion, reconfiguration and automation systems. Full automation will be achieved as a consortium of integrated systems with available CAPP and cyber physical systems (CPS). Baheti and Gill (2011) described a CPS as a new generation of systems with integrated computational and physical capabilities that can interact with humans through many new modalities. Research shows that cloud-based CAPP applications use smart technologies such as the IoT in the production space. With the advent of the era of Industry 4.0, CPS provide a platform for the integration of computing elements with the physical components and processes (Naoufel, 2019). CPS improves productivity and quality through smart prognostics and diagnostics using big data from different networked machine systems sensors. The critical aspect in the design process of the RGS&BPM is identification and definition of the required function. The machine has two functions:

(1) cutting; and

(2) bending, giving the machine dual functionality.

A choice for manual and automatic reconfiguration is available for the chosen function. Automatic reconfiguration can be achieved through a software programme having algorithms and decision matrices. In the design stage a required function must be identified or chosen. Designing then follows the operational parameters or requirements of the chosen function. To enable dual functionality the machine must have a conversion system that is used to change the machine from one function to another. This application can be automatically executed through available software and control system. Figure 3 gives an overview of the design and reconfiguration synthesis for the RGS&BPM. Once the function has been selected, the machine is checked for a conversion need, this is dependent on the



Source: Adapted from Gwangwava, 2014

Figure 3.
RGS&BPM design and reconfiguration synthesis overview

current machine status. If the machine is in the cutting mode, then the part family of products is identified through the determination of part information that provides similarities to the existing part families. For cutting, part sizes are used to classify parts into families and that provides critical information for reconfiguration needs. Reconfiguration needs formulating the machine modules required for the identified parts. Part family creation is based on algorithms and the approach for the RGS&BPM was formulated in a publication (Sibanda *et al.*, 2019). The algorithm uses dendrograms to identify similarities in parts which are then used to merge parts into families and gradually build them into a single larger family until it is no longer feasible to merge them any further. However, several authors have delved into this area developing various tools for part family generation, examples being (Ghosh and Dan, 2010); (Ashraf and Hasan, 2015); (Wang *et al.*, 2016); (Khanna and Kumar, 2017) and (Sibanda *et al.*, 2019). When the part family has been identified, correct function chosen and the correct machine configuration set for the part family production, then the machine is deemed ready for execution.

If the machine configuration capacity is not adequate for the part family, then reconfiguration is started by identifying the modules necessary to handle the family. All modules are stored in a library from where codes are used to identify them. Once identified the machine is reconfigured and checked for compliance. Sensors are used to help detect any errors such as misalignment, tool holding, machine readiness, etc., before the machine can be used. The two machine functions have different safety features which must be satisfied for the reconfiguration to be approved. For the cutting function, a protective screen, which has work holding devices, including motion and obstruction sensors, must be added to the machine, while in bending these are not required. Under special circumstances, if the required part falls within a certain part family but has features that are outside the scope of available modules, then modules may be redesigned or new ones designed considering the feasibility, cost and lead time; otherwise, it maybe be classified as outside the scope of the machine.

4.2 Function-oriented design approach

From the onset, the machine is set to perform two functions, that is, cutting and bending. To achieve these two functions the machine is designed to be reconfigurable and changes functions based on the strength of the convertibility principle of RMS. In the design stage, it is vital to understand which function holds the key to the structural integrity of the machine; however, the machine must process and respond to both functions with equal efficiency, effectiveness and safety. For the two functions, the machine uses the same modules but different tools owing to different operational parameters. The FODA identifies both functions of the machine and allows for the selection of the required function as defined by the operation required. The FODA methodology structure is based on the six principles of RMSs which apply to the RMTs. The design breakdown can briefly be highlighted as represented in Figure 4. Individual analysis of each principle in relation to the methodology will not be presented but an overall picture of the entire methodology is outlined.

A detailed amalgamation of events and the sequence in the FODA methodology is highlighted in Figure 5. The FODA methodology is driven by synchronising two machines into a single RGS&BPM with dual functionality. Dual functionality gives the machine a hybrid synergy where it has an option to cut and bend metal sheets as a single unit by using a convertibility characteristic. The methodology identifies the main function of the machine as the machine's required occupation. There are two main functions of the RGS&BPM, cutting and bending of metal sheets. These two functions are achieved through sub-functions that follow a sequence defined by the required action. Sub-functions are action activities of the main function that result in the achievement of a certain output or task, such

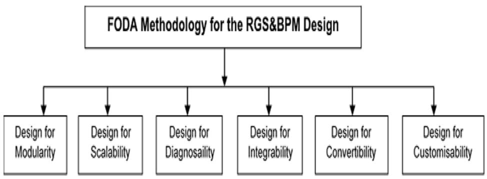
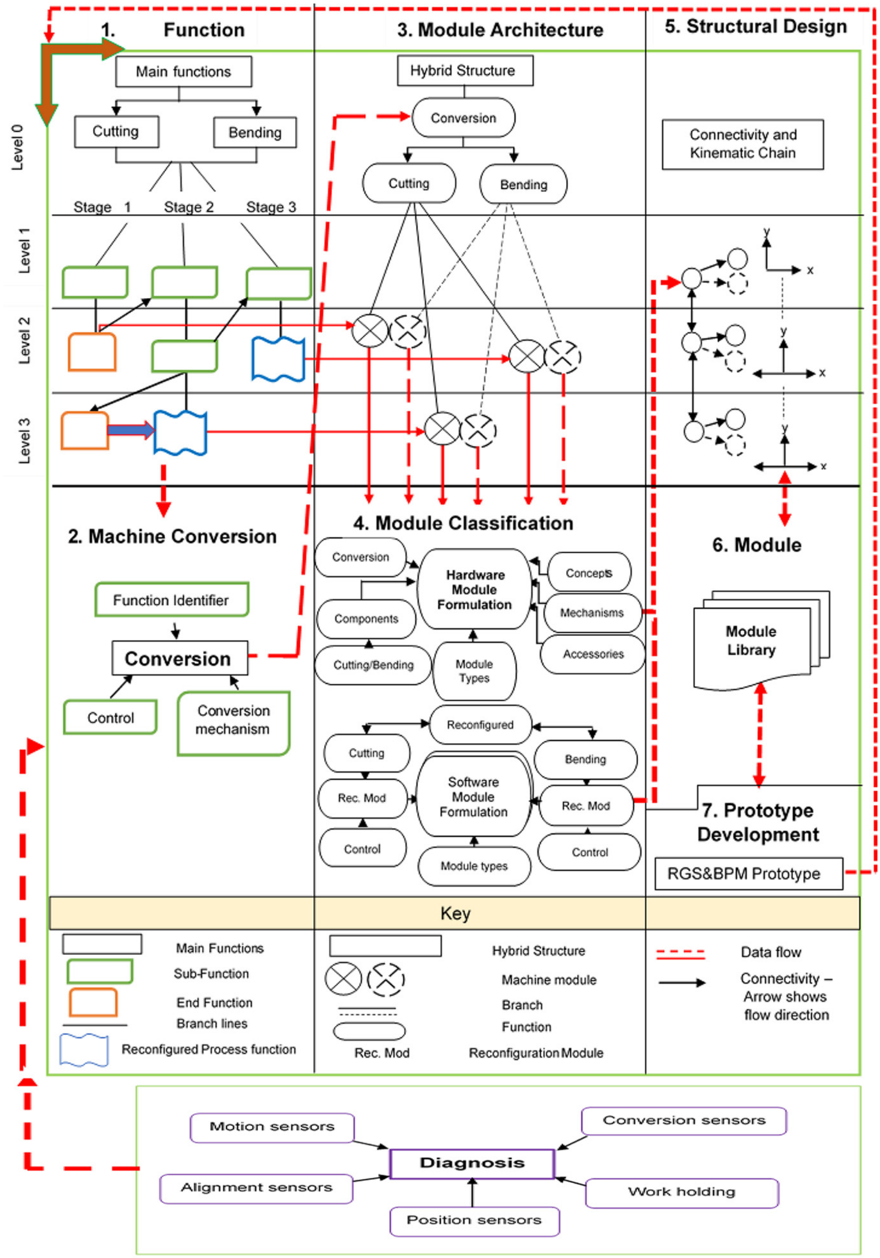


Figure 4.
Structure of the FODA methodology



Source: Modified from Gwangwava, (2014)

Figure 5.
Steps in the FODA methodology

as cutting or bending. There are 3 stages in the subfunctions. Stage 1 refers to the first configuration; Stage 2 refers to the first reconfiguration; and Stage 3 refers to the second reconfiguration which gives the machine its longest length of 4.5 m. Subfunctions are ended by end functions. An end function in this case refers to a scenario where there is no longer any possibility to further subdivide the end function; hence, it becomes a module (Gwangwava *et al.*, 2014). End functions tell the story of the final state of the machine reconfiguration, also known as the reconfigured process function (RPF). When an end function does not satisfy the desired production requirement, then the system looks at the next subfunction and query its suitability for the task.

This signifies the sequence of the subfunctions which is depicted in Figure 2 starting from Level 0 to the lowest level, nth level. Level 0 defines the main functions, while Level 1 and beyond define subfunctions cascading downwards to the lowest level possible. For instance, if the end function in Stage 1 Level 2 does not meet the task requirement, the designer identifies the next appropriate option, which is, Stage 2 level 1. Level 2 signifies a need for reconfiguration, once the machine is properly converted and reconfigured, then Stage 2 Level 3 becomes the end function and a signal is sent for structural adjustment in the Hybrid Structure of the Module Architecture, Stage 3.

In each function the machine length can be increased or reduced to change its capacity, that is, it can be reconfigured. The reconfiguration is embedded in the subfunction of each function. The machine has three horizontal stages of reconfiguration, namely, 1.5, 3.0 and 4.5 m. This means that for each function the machine can be reconfigured to any of the lengths outlined, depending on the requirement and designers base this reconfiguration on part families that the machine is required to accommodate. As the design is for a hybrid machine, conversion is very critical in enabling the machine to change from cutting to bending.

To initiate the conversion process, the design has a mechanism that identifies the existing function, function identifier. This assists the designer to know the function to convert to. A control system controls the conversion mechanism, which is a motorised system. Converting the RGS&BPM translates the conversion into a function architecture that alters the machine hybrid structure by instituting certain movements on module positions of the top beam and ram. The conversion process is preceded by a concept generation and scoring process in determining the most suitable method of conversion. Three possibilities were used in this respect and the rating using several attributes was done using Fuzzy AHP and finally scoring using Pugh Matrix.

The hybrid structure of the RGS&BPM is a machine frame or super structure upon which all working components are mounted and provides a platform for both cutting and bending operations. Machine modules that define the machine configuration are all mounted on the superstructure of the RGS&BPM. Several structural frames are available for these machines. Selection choice is based on certain requirements such as, rigidity, accessibility, robustness and according to Gwangwava *et al.* (2014) envelop size and reconfigurability. According to Moriwaki (2008), there are three types of machine tool frame structures for milling machines, the vertical, horizontal and double column structures. Other structures available are vertical and horizontal knee milling machines frames and vertical lathe machine tools frame structures (Koenigsberger and Tlusty, 2016). For guillotine shears and bending presses, C or gap type and the closed or O-type frames are generally used (Koenigsberger and Tlusty, 2016). Frame types like the H-frame/Straight Frame are available for guillotine shears, while some machine tools have inclinable frames. However, all frame types have their own limits that present certain advantages and disadvantages, particularly in the conversion and reconfiguration processes. For the RGS&BPM, the most suitable frame is the H-frame, which allows for rigidity, conversion and reconfigurability flexibility. A detailed structural model of the machine incorporates a combination of components, module types and relationships, mechanisms and concepts for the reconfiguration process.

Linking these activities are branch and data flow lines. Subfunctions and end functions define the action which is determined by the part family targeted. They are linked up with the conversion and hybrid structure of the machine leading to the identification of modules and accessories required to carry out a task according to part specifications and part family groupings.

4.2.1 Module classification. In Stage 4 modules are selected and classified through the decomposition of the required machine operations. The process defines the type of modules and reconfigurations needed. Modules are stored in a library where they are grouped into four main categories, namely, mechanical, motion, software and control. Functional modules are mechanical devises or structures used to alter the machine structural length through adding or removing them from the main structure to enable capacity changes in both cutting and bending operations. To effect reconfiguration, modules must be identifiable, and this is possible by using classification codes for each module in the library. Classification of modules and components is performed in several ways and an example of a coding systems is shown below:

- 66-45-2013 and 66-50-1220

The description of the code is:

- 66 refers to hardware modules (this forms a class for all hardware modules).
- 45 refers to the cutting function (this is only applicable to modules use in the cutting function).
- 20 refers to the physical component. (component identification).
- 13 is the series in that class (the series is limited by the number of modules in the class).

The second code, 66–50-1220:

- 66 is the same as in the first one, hardware modules.
- 50 refers to bending function and other numbers are descried in a similar manner as in the first code.

Software modules are also identified using a different class from hardware modules, for example, class 87, with other digits used to define certain attributes. Finally, a decision is made on the success of the classification process of the modules and can be revisited if changes are required. Table 2 highlights module types.

Modules work in conjunction with accessories which are also stored in the library and codes are used to identify them. Types of accessories include slides, work holding devises

Series	Module type	Type
1	Mechanical	Hardware structural mechanisms and modules
2	Power	Motive power to provide motion
3	Control	Synchronise machine operations
4	Software	Integrate all hardware mechanisms and control system

Table 2.
Module types

(including their connectivity activation/deactivation connectors), cutting safety features activation/deactivation, motion sensors and other pluggable devices for ancillary motions, Table 3.

There are specific requirements that play critical roles in the whole process, such as machine or module limits. These include the fine adjustments for the xyz-alignments of the moving members, response and measurement sensitivity. The limits set the boundary conditions for the conversion and reconfiguration mechanism definitions. Table 4 gives an overview or reconfiguration mechanisms. They provide a means to identify and counter the machine's inabilities. There are design variables used in this methodology, which are defined as the number of modules, both hardware and software, their positions, and the number of sensors for a selected functional application. These variables are described using Cartesian coordinates. The coordinates are factored into the design through the structural design phase in Stage 5. The designer adds requirements to the model for individual sizes, shapes and their combinations.

Structural design highlights the machine structure based on connectivity and kinematic chain. In this process modules are combined using a module combination set parameters and regulations. Stage 5 gives a representation of the connectivity and kinematic chain process with nodes representing the component or part modules of the machine and kinematics relations between them. A proposed structure is modelled, and a decision is made if it satisfies the process. If it does then it is stored in the library, but if does not, the process is revised until an acceptable outcome is achieved. These activities are connected and controlled through control modules.

All machine functions have software and control modules that work in conjunction with all sensors to ensure that all parameters for any functional application are met before execution. All the sensors are categorised according to a specific need in the machine's operation and regulated under the diagnostic principle of the machine subfunctions. The diagnostic capability also provides information such as proper conversion, alignment, tool positions and speed, among others. The diagnostic principle in the system identifies any out of specification working that produces defects and flags such mishaps to enable minimisation of defective output. It enhances the machine safety systems and problem identification during or prior to execution.

Table 3. Reconfiguration accessories

Series	Device
1	Conversion mechanisms – drive motors, rack and pinion gearing, slides
2	Attachments for tools (components)
3	Concepts: Solution choices
4	Reconfigurations mechanisms
5	Accessories – protective screens, work holders, fittings

Table 4. Module mechanisms for reconfiguration

Reconfiguration need and position	Reconfiguration mechanism
Displacement	(x, y, z, θx, θy, θz)
Vertical	Stroke adjustment displacement
Horizontal	Length adjustment (lengthen or shorten)
Angle	Clockwise or Anti-clockwise rotation
Cutting or bending Force	Increase or Decrease
Size (workpiece length, width and thickness)	Increase or Decrease
Execution	Active or inactive (software modules)

Source: Adapted from: Gwangwava *et al.*, 2014

One of the key features of the module selection process is concept generation. Several concepts are generated and rated to identify the best concept to be developed. This is dependent on the degree to which it meets the desired requirements, after which components and mechanisms are then identified to go with the chosen concept. A link is then developed to merge these with relevant accessories that fully configure the machine to execute the chosen function. At the same time the software/control system is activated to synchronise the machine functions. Successful integration of these items gives a decision matrix that leads to the connectivity and kinematic chain response and thus defining the direction required for the reconfiguration process considering the existing machine configuration under the structural design category. As this is an iterative process, continuous reviews are made to ensure that the machine has been reconfigured and this is enhanced by the diagnostic system. Figure 6 illustrates a detailed flow diagram of the module classification and structural modelling processes. As has been highlighted previously about the dual functionality of the machine, the fundamental action is defining the required function to marry correct accessories and components that suit the chosen function. Finally, once a choice has been made, the reconfiguration process will follow similar processes although the accompanying software will be specific to the function required as they have operational differences. Incidentally, the cutting function requires more accessories than bending although the general reconfiguration process follows similar steps.

5. Reconfiguration needs

The reconfiguration needs for the RGS&BPM are the requirements needed to change or alter the machine structural composition to satisfy a certain output need. This requirement in this context is length adjustment and a partial height adjustment. Length adjustment manifests itself in the change in the overall length of the machine to accommodate a specific part family, while the partial height adjustment merely refers to stroke and or throat adjustment to take on different thicknesses of metal sheets. The primary aim of this is to adapt the machine functionality by changing its structural geometry to suit the production of a new part or part family, hence, the machine's ability to change capacity by adding or subtracting hardware and software machine devices. Figure 7 outlines the reconfiguration requirements for the RGS&BPM. The reconfigurable needs are used to model the RGS&BPM requirements that feed into the decision for reconfiguration, hence, determining the modules and accessories necessary for the part or part family production. A reference is made to the hybrid structure of the RGS&BPM, which then cascades to the module classification and selection, necessary to develop a final machine combination that will be used to produce a given part family. Consideration is taken of the tooling and tool holders for all operational arrangements.

5.1 Machine reconfiguration

After developing modules and part families, the machine is evaluated for reconfigurability in both functions, though not concurrently. This includes the assessment of the prevailing configuration and its suitability for the job at hand. Part or part family dimensions and features of the products are used in this assessment. For example, for cutting, the size (thickness and length) of the part or product to be produced is used, while for bending, thickness, length and part features are used. To determine the machine configuration, an example, equation shown below (although detailed equations are not part of this paper) is used to relate the part length and machine configuration (Sibanda *et al.*, 2019):

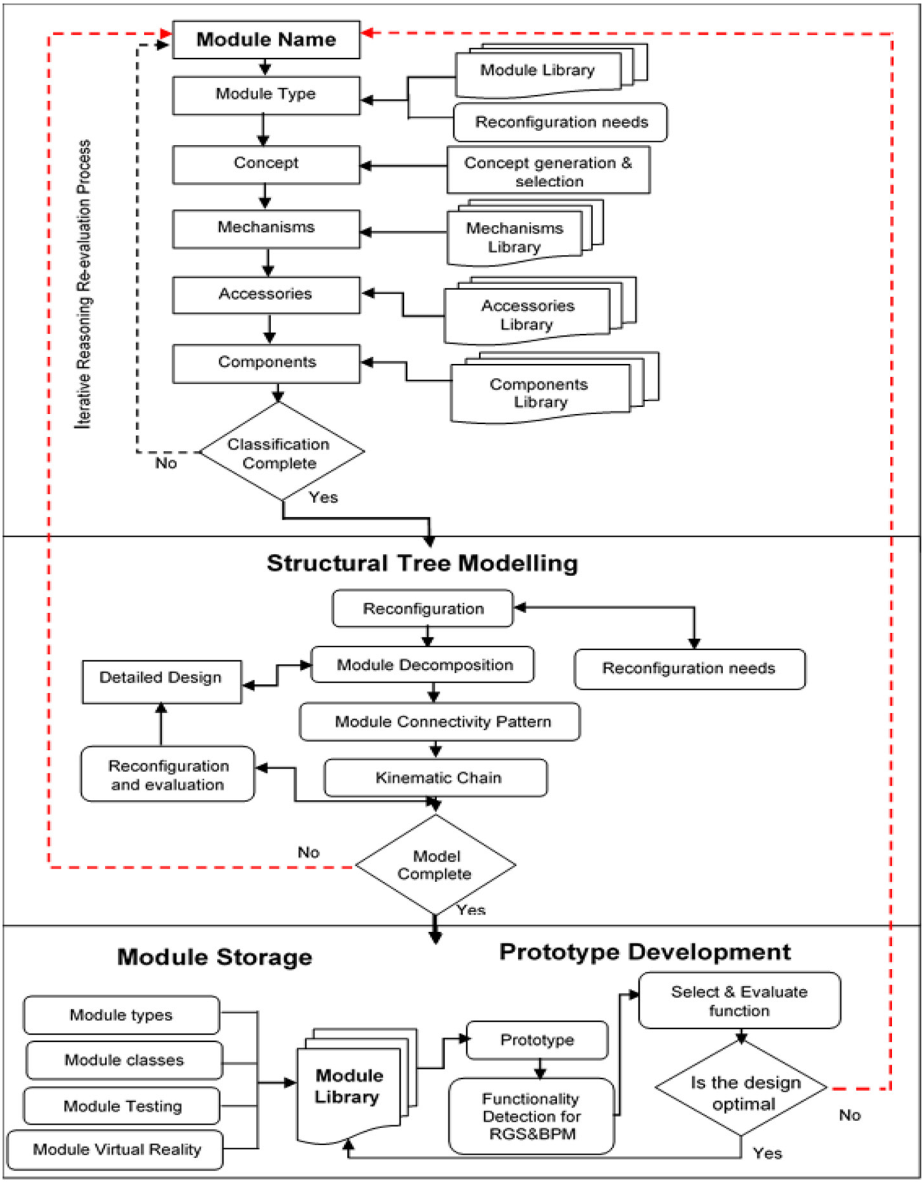
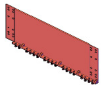
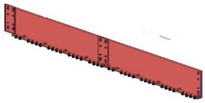
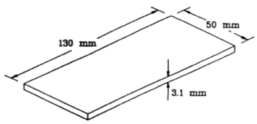
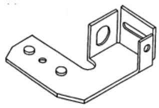
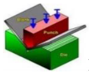


Figure 6.
Module classification and structural modelling processes

Source: Adapted from Gwangwava, 2014

Design	Reconfigurability	Reconfigurability Length	Explanation
Geometric transformation Or Convertibility (Changing from one function to another, i.e. cutting to bending)	Vertical (Throat gap determination according sheet thickness) Length (length of the workpiece determines number of modules to be added) Vertical stroke adjustment in bending to accommodate varying die sizes and sheet thickness	 Single module  Two modules added together Adding or removing modules changes horizontal length of the machine	Machine length is determined by the length of the workpiece. If a short length is required only a single module of the machine is used. With the increase in length more modules are added to reconfigure the machine for the new requirements. For instance, a single module may take a workpiece up to 1metre in length and an increase means adding another 1m module making the machine 2m long and so on. The size of the sheet determines the number of modules to be added to increase/reduce capacity.
The machine works as a Cutting machine and then converted to a Bending press after cutting the sheet, thus giving the machine dual functionality	Horizontal	Length extension	Extension: Increase or decrease in length
	Cutting determined by size and Bending is determined by size and profile  Sheets cut according to requirement  Bending as per required features	Modules (M) added or removed to accommodate sheet length. L = M1 +M2 +……… L = M – M2 - ………. Height configuration is fixed in this instance, but the daylight opening is determined through sheet thickness. The horizontal configuration is determined by sheet length	An RMT is a single machine with modules added/removed to change length instead of tandem machines placed adjacently  Machine configuration 1  Tandem machines
Productivity tuning	Product configuration: Machine conversion - Cutting to bending press and vice versa. Module addition/subtraction to change machine capacity	After choosing the operation required: Hardware and software modules are added or removed to meet the operation required.	Dedicated machines can be operated in tandem though not convertible, but using a RMT only one machine is required with varying configurations using hardware and soft modules.

Source: (adapted from Sibanda *et al*. 2019)

Figure 7. Reconfiguration needs for the RGS&BPM

$$C_i = \begin{cases} 1 & if \quad i \leq 1.5 \\ 2 & if \quad 1.5 < i \leq 3 \\ 3 & if \quad i \geq 3 \end{cases}$$

$$Subject\ to \quad = 0 < t \leq 6$$

where:

C_i = machine configuration;

i = sheet length; and

t = metal sheet thickness (mm).

The machine is designed to take a plate of maximum 6 mm thickness. The impact of the sheet thickness lies in the stroke and throat gap adjustment. On the other hand, sheet size is needed in determining the machine configuration and or reconfiguration. In a case where the required configuration falls outside the scope of the machine, then a design of new modules may be an option, although a feasibility study will be necessary to look at the cost implication and the subsequent lifespan of the machine thereafter. In both scenarios, material type is critical in determining the force necessary for either cutting or bending, if the material is not what the machine was designed for. However, it is vital to note that cutting and bending require different amounts of force. The requisite forces are calculated from the following equations:

For cutting, the force is calculated as:

$$F = StL$$

where:

S = shear strength (N/m^2) or MPa;
t = metal sheet thickness (mm); and
L = length of length of the cut edge (m).

For cutting, the force is calculated as:

$$F = \frac{K_{bf}(TS)wt^2}{D}$$

where:

F = bending force (N);
K_{bf} = Constant;
TS = tensile strength of the sheet metal (N/m^2);
w = width of the part in the direction of the bend axis (m);
t = stock thickness (m); and
D = die opening (m).

5.2 RGS&BPM cutting function tree

The cutting function generally precedes the bending function. The function tree diagram is represented in Figure 8, as it is generated in line with FODA methodology guidelines. The functional requirements are developed for the RGS&BPM for cutting a family of sheet metal parts in preparation for the bending function.

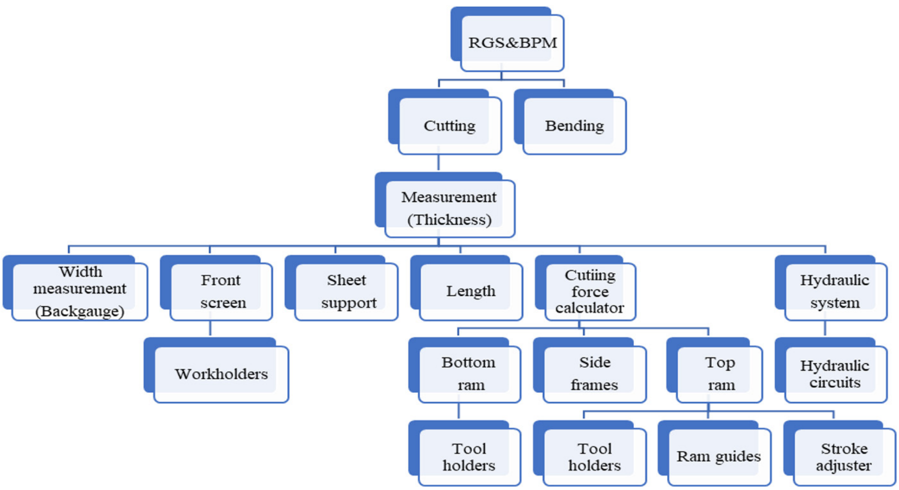


Figure 8.
Cutting function tree

5.3 RGS&BPM bending function tree

The cut part (blank) is taken for bending to convert it into features required for the product. Figure 9 shows the function tree for the bending process. Similarly, the function tree is generated according to FODA methodology guidelines. The functional requirements are developed for the RGS&BPM for bending a family of sheet metal parts as a final operation in sheet metal fabrication, despite painting and other finishing related activities.

5.4 Machine loading sequence

The FODA methodology requires that the machine be subjected to a predetermined sequence of events to achieve a required output, all preceded by function determination or definition. This is started by output product identification and the associated part family with suitable modules. The classification process requires a decision-making tool in the form of software that has all the attributes of module classes, part families, module libraries and accessories for various machine configurations. Each of these is identified by a code that is peculiar to a certain requirement, as outlined in subsection 4.2.1. Figure 10 depicts a sequence of events in machine loading.

A chosen function is accompanied by part parameters which are defined in terms of material, size and part family for the cutting function and material, size, part features and part family for the bending function. An available free machine is detected through a machine loading schedule in terms of machine numbers. The identified machine is interrogated for reconfiguration requirement according to the part or part family. A decision is made based on the machine configuration, showing the next stage as either reconfiguration or loading. Reconfiguration is dependent on availability of suitable modules. If they are not available, then the process goes back to the starting point where it can be determined whether the job falls within the machine capability, the red dotted line refers in Figure 10. If it is within scope, then appropriate modules are identified, the machine reconfigured and evaluated for suitability. Additionally, a concurrent diagnosis process cheques the machine alignment, safety features and other important aspects, after which the machine is loaded when all is in order.

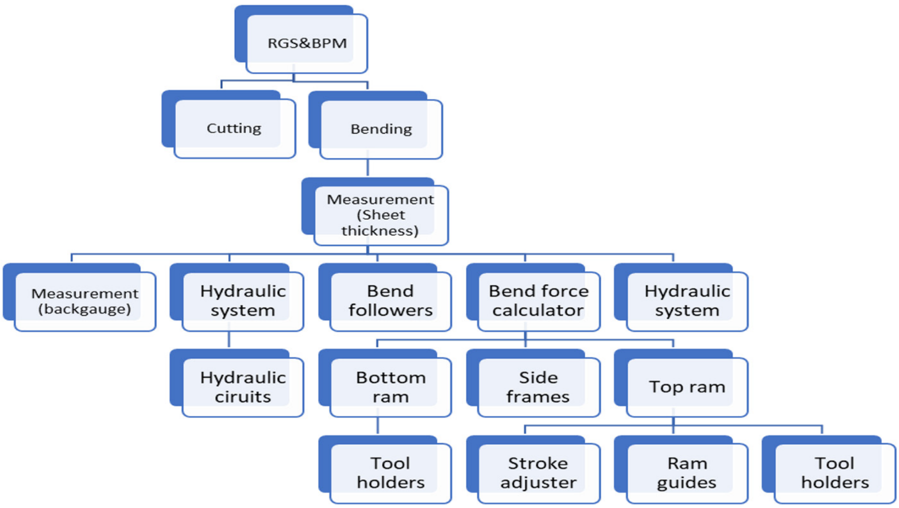


Figure 9.
Bending function tree

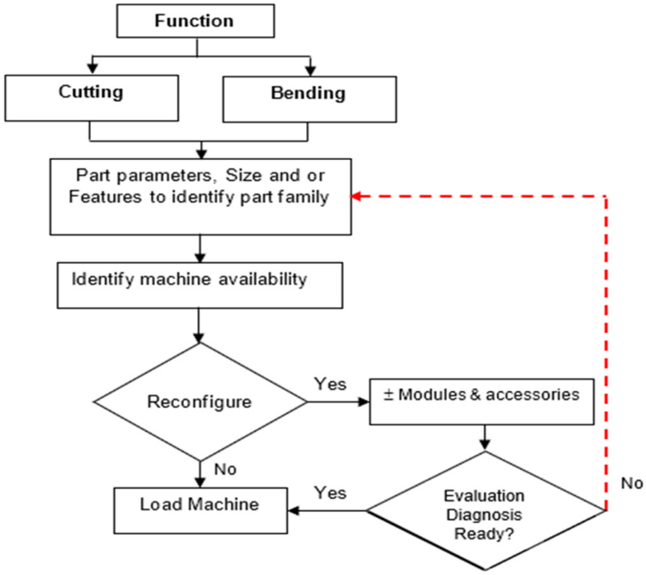


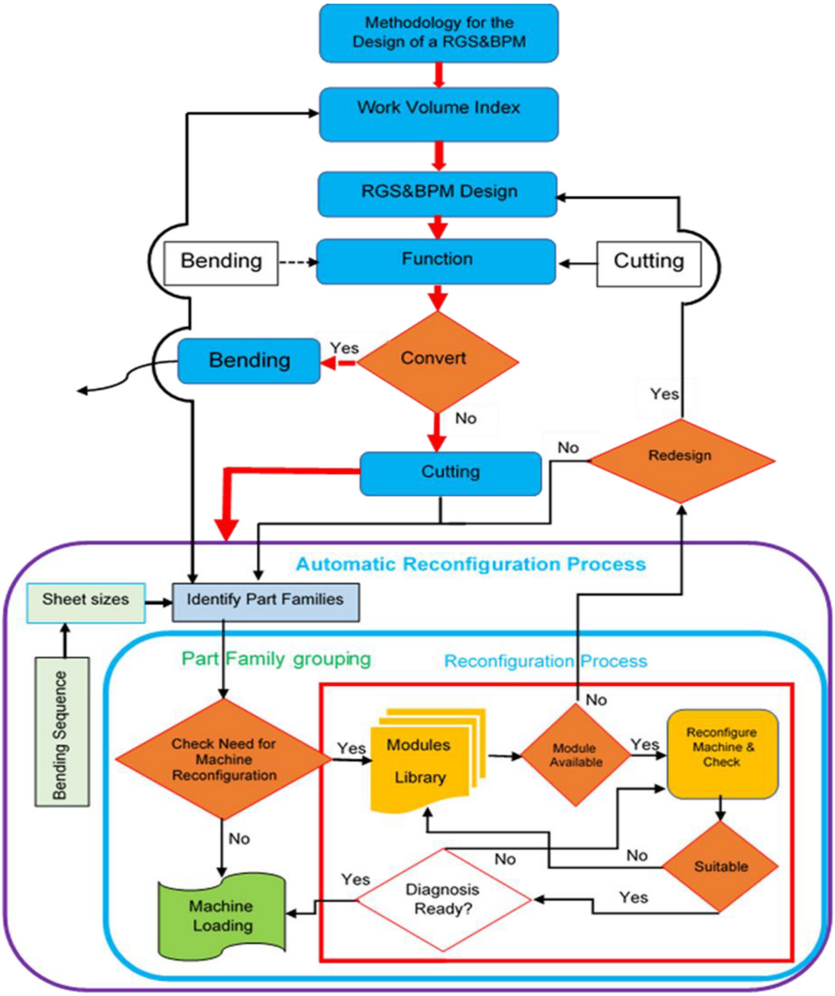
Figure 10.
Machine loading process flow

5.5 Automatic reconfiguration
The machine is equipped with a choice for manual and automatic reconfiguration. Automatic reconfiguration can be achieved through a software programme having algorithms and decision matrices. This is preceded by choosing a suitable function which enables the machine to conform to the operational requirements of that choice. Figures 5 and 6 represent the three-tier relationship comprising the sheet size (length, width and thickness) recognition (with an inherent decision tool), part family grouping and the reconfiguration process. Arrows show the process flow and decisions made. Figure 11 depicts the cutting function scenario while Figure 12 signifies the bending function scenario.

Machine reconfiguration is a two-part process which starts by naming a required function and then determining the machine configuration which will determine the need for conversion. The second part is defining the part family and requisite modules (both software and hardware) required. These modules are either added or subtracted to create the actual machine configuration suitable for the exercise. For the RGS&BPM, reconfiguration is only for increasing or decreasing the machine length. Height reconfiguration is purely the adjustment to suit the workpiece thickness in terms of the throat gap or stroke length. Automation of these processes ensures an increased responsiveness and reduced ramp-up time, increased and optimised operation to match the production requirements and process plan.

6. RGS&BPM CAD models

To achieve both cutting and bending, the machine is convertible. A successful concept development of this machine has been achieved. Several concept selection processes were interrogated in the design phase of the machine and selected ones were the Fuzzy Analytical Hierarchy Process (FAHP) and the Pugh Matrix. FAHP was used to narrow down the scope of deduced criteria and get the weights which were then subjected to the Pugh Matrix for the final selection process. Shown in Figure 13 are the FAHP



Source: Modified from Gwangwava *et al*., 2014

Figure 11. Design and reconfiguring the RGS&BPM for bending

concepts and related criteria used. The design focusses on developing a machine with dual functionality that can accommodate metal sheets of varying lengths and widths as has been elaborated. Figures 9 and 10 have cemented this analogy as supported by several contributions in the research. Reconfiguration is achieved through modules such as top beam, top ram, bottom ram, worktable, protective screen and hydraulic cylinders.

These hardware modules are supported by software modules that synchronise and ease the execution of the required functions. Figure 14 shows a CAD model machine in primary cutting state before reconfiguration. The attached red screen is the protective screen with work or sheet metal holding devices and safety sensors necessary for the cutting function.

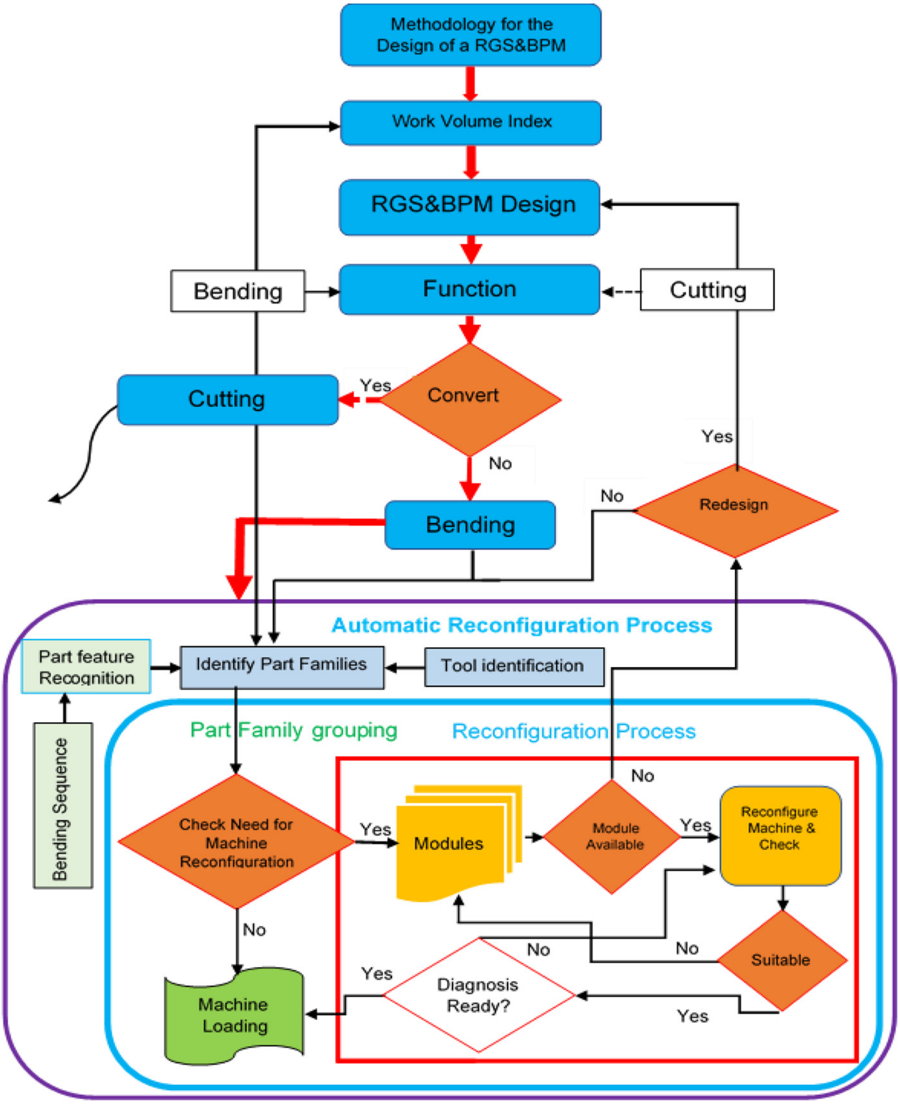


Figure 12.
Design and reconfiguring the RGS&BPM for bending

Source: Modified from Gwangwava, (2014)

Figures 15 and 16 show an illustration of the RGS&BPM CAD model configurations using modular units. The figures show a reconfigured RGS&BPM with one modular insert having been used to increase the length of the machine for both the cutting and bending functions. The reconfigurability is achieved through the insertion of modular-base inserts for the top beam, the top ram, the bottom ran, the worktable, hydraulic cylinders and the protective screens (when cutting), to extend the length of the machine. For ease of coupling the modules, modular units are created with a step on both ends that fits and mates into each other and dowel pins are used for their accurate location. This minimises the alignment time and facilitating a perfect fit during reconfiguration. The mated inserts are then bolted firmly together resulting in a rigid and solid structure. Hydraulic cylinders are mounted on each additional beam added and coupled to the top ram.

The hydraulic system has a separate reservoir and pump unit which are not fixed to the machine structure. A detailed design process for the machine structure is handled through the methodology shown in Figure 6 in subsection 3.2.1. A detailed account of the process selection method for the machine components interface, hydraulic modelling and calculations for the mechanical and electrical parts has not been included in this paper. In operation, prevailing conditions may warrant recalculation of some machine parameters to facilitate changes that may be prudent as dictated by the operational environment. This may eventually see a regeneration of some CAD models based on process and operational requirements. These will be linked to the module library database to enable identification of the correct modules in relation to available part families. Generation of part families may result if compatible ones are not available in the library, provided they fall within the scope of the machine.

The fabrication process of different modular units is determined by the type of unit, its complication and material used. However, for critical components like the machine frame,

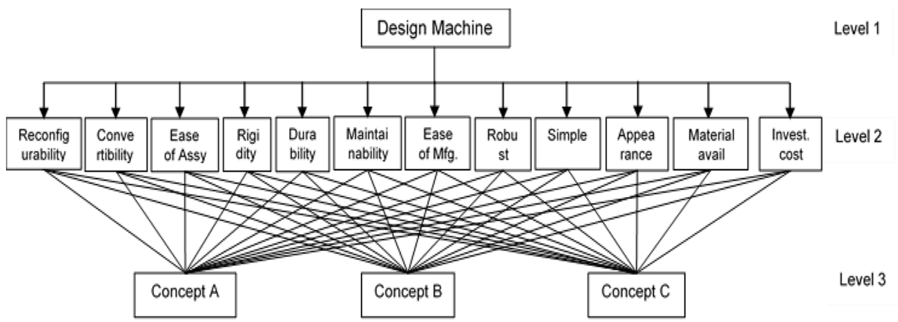


Figure 13.
Hierarchical structure for the concepts

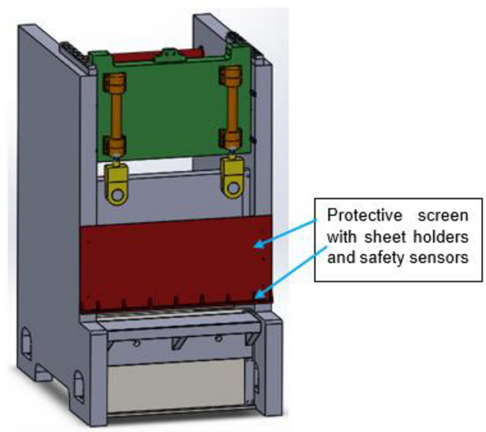


Figure 14.
RGS&BPM before reconfiguration

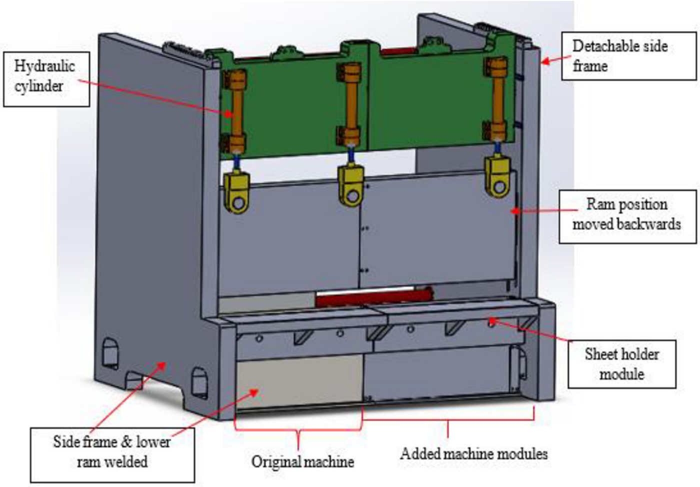


Figure 15.
Reconfigured RGS&BPM (cutting)

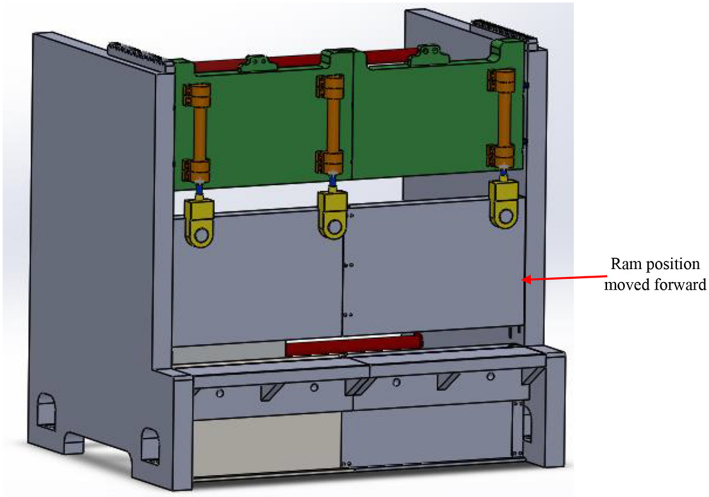
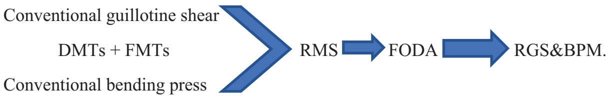


Figure 16.
Reconfigured RGS&BPM (bending)

the bulk deformation process is used, especially rolling. Some methods available are casting, forging, injection moulding and machining.

7. Conclusion

A FODA methodology for the RGS&BPM design has been presented and explained with the aid of a conceptual model. In the methodology, an approach is presented for designing, converting and reconfiguring, in terms of length, the RGS&BPM. The machine provides an alternative to having two machines, which would require more space, energy, labour and more capital to achieve an initial investment. The current practice is having a guillotine shear and a bending press that are of fixed capacity and when capacity and customer needs change, as is the norm now, then a new investment is required. The targeted group for this technology is the small-to-medium enterprises (SMEs) that will grow with the machine by procuring modules as the business grows. However, the design is not limited to SMEs, but other sheet metal manufactures a well. This offers a choice where sheet metal practitioners can use the reconfiguration advantages of the machine to accommodate a given number workstations. Machine design calculations have been left out in this paper, as it only demonstrates the method and concept development. It also highlights the adoption of the FODA methodology on the design phase. Attention has been given to the conversion and reconfiguration phases in the design process. Process planning and part family classification have not been covered although they form a critical part in RMSs. A prototype of the RGS&BPM provides an experimental platform for the implementation of these parameters. A flow chart for machine loading and module selection was provided, and the implementation of the diagnostic principle will create a new dimension in the analysis of the responsiveness of the RGS&BPM. The FODA methodology is based on all the six principles of RMS; hence, it gives the designer an approach that can fully adhere to RMS requirements and for implementation in the design of modular reconfigurable machines. In the final analysis, the FODA methodology, born from RMS principles to give RGS&BPM, can be summed up as shown below:



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Corresponding author

Vennan Sibanda can be contacted at: vmsibanda@gmail.com