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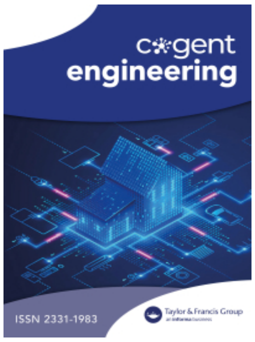

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Experimental validation of a reconfigurable guillotine shear and bending press machine

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Abstract: The reconfigurable guillotine shear and bending press machine is a dual-functional machine that combines cutting and bending processes in sheet metal processing, minimising the time required for set-up and operating seamlessly. The objective of this study is to carry out the performance evaluation of the cutting and bending operations of the developed machine using physical experimentations with aluminium 7075 sheet metal. The cutting and bending processes were conducted successively using the developed machine under pre-designed operating conditions. The thickness of the aluminium sheet metal was 0.5 mm, while the velocity of the guillotine was kept constant at 0.015 mm/sec. A constant cutting force of 25.6 kN and a constant bending radius of 2 mm as well as varying bending angles (30–90°) and bending forces (5–15 kN) were employed to investigate the total time taken for the bending and cutting operations as well as the effect of the bending angles and bending forces on the springback phenomenon. The lowest bending angle (30°) has the highest springback factor of 1.43 under a bending force of 5 kN, while the highest bending angle (90°) has the lowest springback factor of 1.11 under an optimum bending force of 10 kN. The percentage difference in the time saved using the developed machine ranges from a minimum value of 58.66% to a maximum value of 60.22%. The results show that there is a direct relationship between the average time taken and the bending angles for the bending operation. Conversely, for the cutting operation, a direct relationship was observed between the average time taken and the cut angles. The results obtained also indicate that higher bending angles reduce the springback phenomenon but with an increase in the time taken for the bending operation and vice-versa. The results from the physical experimentation provide insight into the effectiveness of the machine in meeting its service and functional requirements.

Subjects: Industrial Engineering & Manufacturing; Mechanical Engineering; Manufacturing Engineering; Production Engineering; Technology

Keywords: aluminium 7075; bending; cutting; guillotine; reconfiguration

1. Introduction

Nowadays, manufacturing companies are faced with increasing market dynamics amidst emerging technologies, changing customer requirements and increasing competition. Thus, to meet the bottom line of profitability, they must embrace technological innovations aimed at reducing manufacturing lead time and promoting product quality. The bending and cutting of sheet metal are one of the most widely used industrial processes, for product forming which finds application in the automobile and aircraft industries amongst others (Prabhakar et al., 2013).

In the sheet metal working industries, there are generally two main operations conducted, the first one being the cutting of raw material into predetermined sizes, and two, forming or bending of the cut sheet material into predetermined part configurations as defined by the application. To conduct these operations, two separate machines are often required. The first is either a laser or guillotine shear which cuts sheet metal into predetermined sizes, and the second one is a bending press machine which bends the cut sheets into predetermined profiles. For Small and Medium scale enterprises, the costs of procuring, operating and managing the two machines are rather prohibitive. The time it takes to set up different machines for cutting and bending operations may also increase the total manufacturing lead time thereby reducing the time and cost-effectiveness of the manufacturing process (Sibanda et al., 2017, 2021). Furthermore, other constraints may also include the space allocation to the machines and the amount of energy consumed by the different machines during manufacturing operations. An attempt to solve these identified constraints led to the development of a reconfigurable guillotine shear and bending press machine that integrates the cutting and bending functions into a single machine. Its reconfiguration features, based on six principles of Reconfigurable Manufacturing Systems (RMS), namely modularity, scalability, integrability, convertibility, customisation or flexibility, and diagnosability, enable the developed machine to respond rapidly to changes in capacity, and functionality to meet the dynamic demand in product requirements (Koren et al., 1999). Koren & Shpitalni, (2010) defined the reconfigurable machine as machines with modules that can be adjusted to provide either alternative functionality or incremental increase in the rate of production to meet changing demand.

To meet the various changes and requirements that characterise the manufacturing processes in this digital era, cost-effective reconfigurable systems are developed. Thus, the reconfigurable machines have two objectives. The first objective is adaptability, which refers to the degree of the machine's flexibility and responsiveness to manufacturing changes, and the second objective is to adjust the machine's production rate by removing or adding modules or resources to meet current demand.

Sheet metal cutting and bending processes require changeable and adaptable systems to reduce production cycle time and operations costs (Yoon et al., 2014). To achieve a short cycle of responsiveness, the reconfigurable machines are designed to ensure effective reconfiguration that meets current production requirements (Eriyeti Murena et al., 2021). According to Mittal and Jain, (2014), some of the performance indicators of a reconfigurable system include ramp-up time, cost-effectiveness, machine reliability and availability, reduction in manufacturing lead time, and reconfiguration time effectiveness. Many authors have attempted to explain the principles of reconfiguration in six dimensions namely: modularity, scalability, integrability, convertibility, diagnosability, and customisation (Al-Zaher, 2013; Daniyan et al., 2019; Koren et al., 1999; Krishna & Jayswal, 2012; Malik et al., 2021; Moghaddam et al., 2018; Olabanji & Mpofu, 2020; Sibanda et al., 2022; Wiendahl et al., 2007).

Modularity refers to the creation of detachable unit structures known as modules that can be added/removed, replaced, or upgraded to suit new applications. Scalability is the variation or modification of the machine's production capacity either by scaling it up or down through the addition or removal of modules. Integrability refers to the precise integration and linking of the different modules through mechanical, software, information and control interfaces to produce a single fully functional machine after reconfiguration. Convertibility is the ability of the machine to easily change from an existing functionality to another in response to new production and market requirements. Reconfigurable machines are often known to possess the ability to switch from one level of functionality to another as product processing/designs change. Diagnosability refers to the control aspect that indicates the capability of the machine to monitor and identify errors and take corrective action through the use of embedded control technologies and signal processing techniques. The ability to identify errors during the manufacturing process improves the quality of the final product and the integrity of the manufacturing system. Customisation refers to the degree of flexibility that allows the machine to be reconfigured in response to a new part family of products as defined by the machine envelope. This is to enable the production of a specific part or product family.

The six principles of RMS are necessary to achieve the objectives of machine reconfiguration such as improvement in product quality, time, cost-effectiveness, machine flexibility, responsiveness to the market and production dynamics ramp-up. For instance, scalability enables varying the machine production capacity by adding or subtracting modules in response to prevailing manufacturing conditions, thus reducing ramp-up time (Gu & Koren, 2018). Chen et al., (2009), stated that cost-effectiveness is central to the idea of a machine's reconfiguration. Thus, Galan et al., (2007) presented a methodology for facilitating reconfiguration in manufacturing to effectively achieve the six core principles of reconfiguration. (Sibanda et al., 2022) indicated the feasibility of achieving a significant reduction in the ramp-up time and cost with the use of the reconfigurable guillotine shear and bending press machine. Some authors further explored the concept of reconfiguration to invent methodologies and techniques for parts or product family development, configuration features and designs amongst others (Ashraf & Hasan, 2015; Dashchenko, 2006; Shang et al., 2020; Sibanda et al., 2019).

However, not many works have been reported on reconfigurable guillotine shear and bending press machines, machines that can cut and bend sheet metals in succession. The increase in the demand for custom-made products necessitates the need to transform versatile materials such as sheet metal into different profiles. The transformation occurs through the sheet forming processes such as metal cutting or bending to impart the required shape into the sheet metal to form a new product. This study performs experimental investigations to validate the key principles of reconfiguration in a reconfigurable guillotine shear and bending press machine.

Springback or springforward is one of the major phenomena that can affect the precision of the bending operation. This phenomenon is a result of the displacement of the molecules as well as the stress and strain induced in the material. Existing works have reported that the phenomenon can be influenced by a combination of factors such as punch radius, nature and specification of tooling, material thickness and yield strength, bending force and angle, bending allowance, as well as the width of the notch of the bottom, die (Davoodi & Zareh-Desari, 2014; Fang et al., 2014; Lawanwomg et al., 2014; Lee et al., 2015; Li & Lu., 2015).

(Özdin et al. 2014) investigated the effect of bending parameters such as the bending angle and the punch radius on the phenomenon of springback or springforwad for AISI 400 sheet metal. The authors recommended a combination of a high bending angle and a lower punch radius to tackle the springback or springfoward phenomenon. This finding was similar to the results obtained by Dametew and Gebresenbet, (2017). Bakhshivash et al. (2016) however, reported that the phenomenon of springback or springforward during the bending operation can be minimised by increasing the bending angle in combination with a larger punch tip radius. Bakhshivash et al. (2016) argued that the combination of a large bending angle and a large punch radius can promote homogeneity in the strain distribution along the sheet metal with a reduction in the amount of strain developed. Gattmah et al. (2019) investigated a plate bending process by employing a 3-D explicit finite element model for the simulation of the V-shaped die bending process. The two materials considered include Hy-80 steel and 304 stainless steel plates at varying plate thicknesses and punch radii. The finding indicates that the springback phenomenon can be minimised by increasing the plate thickness and decreasing the punch radius. (Khleif et al., 2020) suggested that an increase in the punch hold time for a given thickness configuration minimis to minimise the chances of springback. To solve the effect of springback and springforward during the bending operations, many authors have proposed some techniques such as mathematical modelling, optimisation, machine learning approach, analytical approaches, finite element analysis, and numerical technique validated via physical experimentations amongst others (Andersson, 2007; Kazan et al., 2009; Kim and Koç, 2008; Safaei et al., 2011; Siswanto & Omar, 2009).

Welo and Widerøe (Sharma et al., 2021) mentioned five industrial bending processes, namely: press bending, a high-speed forming procedure that is suitable for volume production, normally employed for comparatively thick-walled sections, bars and open sections. The second is the roll bending for prototyping and other low-volume applications. This is highly designed for large radius bends, but the precision of the bend is quite low due to heavy contact stresses. Thirdly, rotary draw bending is suitable for precision forming at tight radii. This involves a constant bending moment along the bend generating low contact stresses between the part and the tool, thus minimizing distortions. The fourth is the stretch bending which is effective for forming multiple bends in one single setup method applied to high-volume production, and sometimes internal mandrels are used to minimize local distortion. Finally, compression bending is carried out by clamping the workpiece to a die and using a wiper shoe to rotate the profile around the fixed bending die. Dimensional accuracy is low to moderate due to heavy shear forces and lack of stretching. These bending technologies are associated with pros and cons. Some are attractive for dimensional accuracy, while others offer low part cost or tool cost. The reconfigurable guillotine shear and bending press machine perform bending operations at moderately high speeds; however, the bend tolerances and appearance are not very good although these are primarily dependent on the punch and die design.

Configuration optimisation is essential in reconfigurable machine tools. Different optimisation objective functions have been developed for various solutions. Abdi (Welo and Widerøe, 2010) optimised manufacturing configurability (capacity and functionality), total cost (operating cost, overhead, and capital), quality (convenience of use, reliability, accuracy, and compatibility), and performance (efficiency, risk, and safety) using a Fuzzy analytical hierarchical process (FAHP) model with five hierarchical levels to set strategic goals, set objectives and criteria in a hierarchical order, identify available machine/configuration options, trade-off the objectives and criteria with fuzzy/crisp values, and select the most preferred configuration.

According to Mpofu & Tlale (Abdi, 2009), optimisation objectives were conducted through a minimum number of degrees of axes, minimum reconfigurations, and minimum dissimilarities between old and new configurations. The authors considered a method to create dynamic optimal configurations of machine structures through multi-level fuzzy decisions considering part geometry. By adding the necessary auxiliary modules (i.e., auxiliary modules that belong to only the new configuration), eliminating the undesirable auxiliary modules (i.e., auxiliary modules that belong to only the existing configuration), and adjusting the remaining auxiliary modules, an existing machine configuration can be changed into a new machine configuration (Mpofu & Tlale, 2012). The authors performed the Technique for Order Performance by Similarity to Ideal Solution (TOPSIS) approach to rank the nondominated solutions of NSGA-II and to obtain the attribute weights through the Shannon entropy weight theory.

Bensmaine *et al*., (Goyal et al., 2012) optimised total cost (production, reconfiguration, tool changing and operation cost), and the total completion time (processing time of a particular operation, tool change time, and reconfiguration time). Their method was to provide a set of non-dominated solutions using Non-dominating Sorting Genetic Algorithm (NSGA-II) based on the process plan that gave more flexibility to the decision-maker. Xie *et al*., (Bensmaine et al., 2013) indicated that the functions of optimization were based on product quality and production cost. The authors carried out a comparative optimisation model for identifying the optimal RMT configuration based on production process plans using a genetic algorithm (GA). Zhang and Bi (Xie et al. 2012) reiterated that objectives for optimization were focused on the maximum rotational motion of the PKM end-effector. They carried out an analysis of direct and inverse kinematics, through the optimisation of structural parameters based on the genetic algorithm (GA) to get the optimal configuration.

Mostly cutting operations are performed by applying a shear force, which is termed a shearing process (Bensmaine et al., 2013). Most manufacturing industries employ trial and error methodology for quality checks of a finished product resulting in a loss of time and an invertible increase in cost. Thus, faulty products are discovered after production. Machine learning techniques can assist in tackling such problems by increasing resource efficiency and optimizing the process parameters by objective cutting optimization and uniform machining (Li et al., 2000; Rao et al., 2017; Sen & Shan, 2006). Wang *et al*., (Jamwal et al., 2021) proposed a flexible bending machine for bending sheet metal such that there is flexibility between the clearance of the die and the punch required for bending. The clearance can be adjusted by the process parameters within a predetermined range, to ensure that the machine accommodates materials of various thicknesses and shapes. However, the machine is limited to bending operation as the cutting function was not integrated into the machine. For the simulation of the bending process and behaviours of materials, the generalized finite difference method was proposed by Li et al., (Wang et al., 2020), while Zenkour et al., (Li et al., 2020) proposed the use of nonlocal mixed variational formula for bending process analysis. Vinh (Zenkour et al., 2020) presented a new mixed four-node quadrilateral element for bending analysis, while Nguyen et al., (Vinh & Martos, 0000) proposed a quasi-3D theory for bending analysis.

This study focuses on the performance evaluation of the cutting and bending operations of the guillotine shear and bending press machine (RGS&BPM) using physical experimentations with Al 7075 material. It is important to note that this is a new machine that is undergoing performance evaluation after a successful design and manufacture based on reconfigurable manufacturing principles. The machine was evaluated in terms of the time required to carry out the bending and cutting operations, the effect of bending angles on the bending time and springback phenomenon as well as the effect of backgauges on the cutting time.

Exiting works have reported on the optimisation of the machining parameters during the turning operation of Al 7075 as well as the fabrication, interlayer bonding and mechanical characterization of the material (Nguyen et al., 2019; Surya et al., 2019). However, its successive cutting and bending operation and the investigation of the springback phenomenon while using a reconfigurable machine and has not been widely reported.

The novelty of this study lies in the fact that the use of a reconfigurable machine that combines the dual functionality of cutting and bending operations as demonstrated in this study has not been sufficiently highlighted by the existing literature. The cutting and bending processes of aluminium 7075 sheet metal was carried out successively using the developed RGS&BPM under pre-designed cutting conditions. The study further establishes the relationship between the bending angles and the time for bending operations as well as the occurrence of the springback phenomenon. This study provides empirical results for the cutting and bending operations of the RGS&BPM. It is envisaged that the results obtained from the physical experimentation provide insight into the effectiveness of the RGS&BPM in meeting its service and functional requirements. The findings in this study can also assist the sheet metal industries in achieving significant time and cost savings during bending and cutting operations. This is a new machine and its capability needs to be fully investigated and exploited for the benefit of potential end users.

2. Methodology

The flow chart for the evaluation of the RGS&BPM is presented in Figure 1.

The bending process involves the application of force on the aluminium sheet metal to change its geometry. The malleability of the aluminium sheet metal allows it to undergo the shaping process. It is the straining of the sheet metal around a straight edge. The applied force produces

Figure 1. Flow chart for the evaluation of the RGS&BPM.

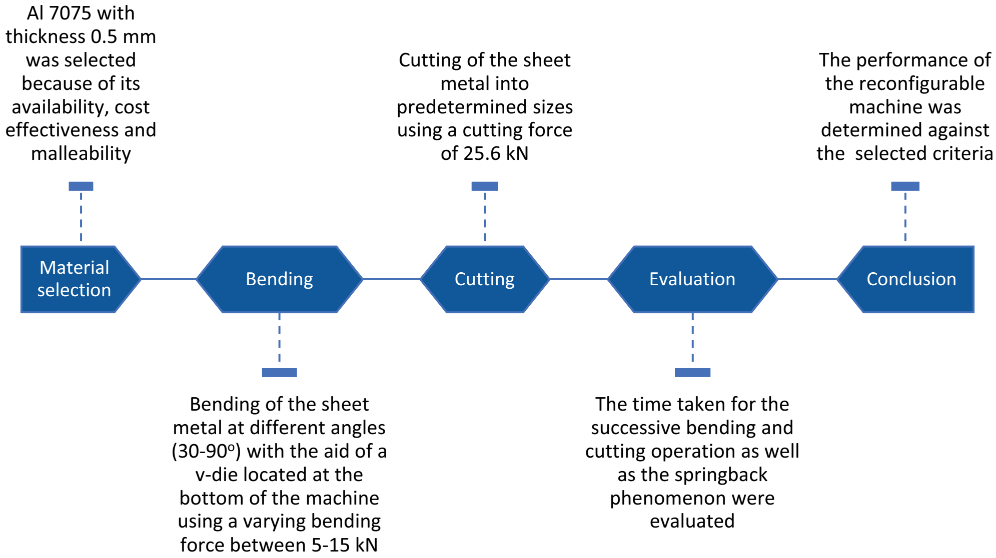


Figure 2. The reconfigurable guillotine shear and bending press machine for cutting and bending operations.

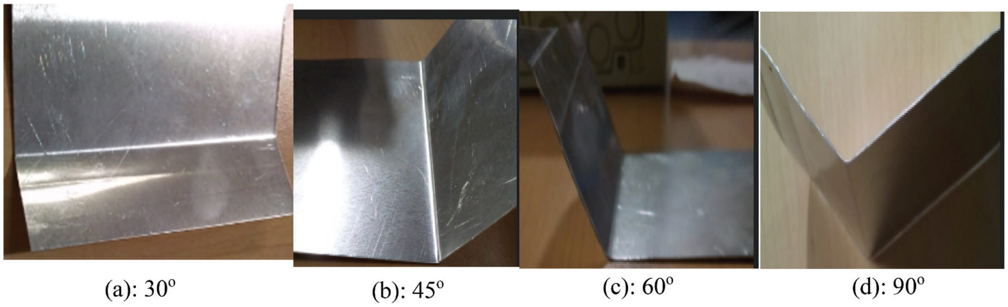
stress on the sheet metal beyond the yield strength of the material thereby causing physical deformation without failure. In a cutting function of RGS&BPM, shown in Figure 2, the cutting blades are lowered to cut the sheet metal trapped between the top and bottom knives. The top knife/blade is held at an angle to reduce the cutting force required and progressively cuts the sheet metal blank to predetermined sizes, like a pair of scissors (Figure 3a). In the bending process, the punch is lowered to the sheet metal that is already positioned horizontally over the v-die located at the bottom of the machine. The punch at the top of the machine forces the sheet metal portion into the "V" groove of the die which has the desired bend angle (Figure 3b). The punch and die both have the desired bend angles for the finished product. There are different angles on the reconfigurable guillotine from which the desired bend angle is selected. Figure 4a-d present the bent

Figure 3. Cutting operation of aluminium sheet fig. 3b: Bending operation of the aluminium sheet.

a: Cutting operation of aluminium sheet

b: Bending operation of the aluminium sheet

Figure 4. The bent aluminium sheet at different angles (30–90°) (a): 30° (b): 45° (c): 60° (d): 90°.


(a): 30°
(b): 45°
(c): 60°
(d): 90°

aluminium sheet at different angles (30–90°). The sheet metal (Al 7075) was supplied by Maxsteel, Gauteng, South Africa.

As shown in Figure 2, the reconfigurable guillotine shear and bending press machine majorly comprise shear support to withstand vibration, the blank holders at the lower parts to hold the sheet metals to be cut or bent, the upper and lower blades employed for the cutting operation as well as the backgauges that are used to ensure that the workpiece is being cut at the exact point with precision. It also has a control panel for the control of the machine and the selection of the cutting or bending parameters. The machine works at a semi-automatic level with some level of human intervention needed to support the automatic controls.

To achieve a cutting and bending operation that meets the designed requirements, there is a need to ensure a high-quality shear, by minimising the effects of variation concerning the sheet metal orientation, internal stresses, and features. This is to avoid quality compromise or defects in the final product.

Table 1 presents the properties of the aluminium 7075 sheet metal employed for the cutting and bending experimentation in this study.

The tensile strength is a critical parameter that indicates the transition of the material from a uniform deformation to a locally concentrated deformation (Adeodu et al., 2020). Before exceeding the maximum tensile stress, the deformation is uniform but thereafter the metal begins to shrink thus resulting in concentrated deformation.

Table 1. Properties of the aluminium 7075 T7 (Surya, 2023)

Mechanical Properties	**Value**
Young's Modulus (GPa)	70
Tensile strength (MPa)	410
Ultimate tensile strength (MPa)	500
Shear strength (MPa)	320
Elongation at break (%)	9.3
Brinell's hardness (BHV)	140
Fatigue strength (MPa)	160
Poisson's ratio	0.32
Thermal Properties	
Thermal conductivity (W/m-K)	130
Specific heat capacity (J/kg-K)	870
Thermal expansion coefficient ($\mu m/m-K$)	23

The deformation due to bending is a gradual process which increases with an increase in the magnitude of the stress induced in the material until the maximum value of the tensile stress is reached (Adeodu et al., 2022). The resistance to deformation thus reduces at the maximum value of the tensile strength of the material causing a large deformation to occur at the weakest part of the section of the material, thereby resulting in bending (Daniyan et al., 2020).

The lowest die opening in the RGS&BPM represents the notch width of the lower die channel. The notch width is taken to be six times greater than the plate thickness by the rule of thumb. Thus, for the aluminium sheet with a thickness of 0.5 mm, and bend length of 50 mm, the notch width is calculated to be 3 mm. During the bending operation, the section of the material inside the bending machine fillet undergoes compression, while the outside section is stretched while the neutral axis remains unaffected. This implies that the dimension of the section of the material inside the bending fillet shortens while the one outside increases. This is in line with the simple theory of bending (Daniyan et al., 2019).

The blade clearance represents the perpendicular distance between the shearing blades. The exact cutting clearance is a function of both the ultimate tensile strength of the material and the thickness of the sheet metal. A small clearance angle increases the chances of blade wear thereby increasing the tooling and maintenance cost. It also increases the cutting force thereby making the cutting process less sustainable. On the other hand, if the cutting clearance is too large, the material is drawn between the two blades resulting in a cut edge with an increased taper and larger plastic deformation. This reduces the quality and finish of the final product. There may also be a need for post-processing in such a case which may increase the time taken for the required operation. Thus, affecting the overall time and cost-effectiveness of the cutting process. This indicates that the cutting clearance is a key factor for the edge quality. As a rule of thumb for aluminium, the blade clearance is usually set at 0.05 mm per each mm of plate thickness up to 10 mm. For instance, in this study, for the aluminium sheet with 0.5 mm thickness, the blade clearance was set at 0.025 mm.

Equation 1 expresses the bending force (Bansal, 2009).

$$F_b = \frac{Wt^2}{L}.T_s \tag{1}$$

Where:F_b is the bending force (N), W is the total width sheared (25 mm), L is the bend length (50 mm), T_s is the ultimate tensile strength (500 MPa) and t is the thickness of the sheet metal (0.5 mm). Using a safety factor of 1.60, the bending force (F_b) was calculated at 10 kN.

Therefore, bending forces of 5 kN, 10 kN and 15 kN were selected for the purpose of investigating the effect of the bending forces on the springback phenomenon.

Equation 2 expresses the strain developed in the material during bending (Shah, 2015).

$$e = \frac{1}{((2R/t) + 1)} \tag{2}$$

Where e is the strain developed and R is the bend radius in mm.

The minimum bend radius is expressed as Equation 3.

$$R = t\left(\left(\frac{50}{r}\right) - 1\right) \tag{3}$$

Where r is the tensile area reduction in %.

During the bending operation, it was ensured that the length of the material matches the total bend dimension and corresponds to the gaps on both sides of the twist.

The bending and cutting operations were carried out successively. For the cutting operation, the machine produces small rectangular cuts from the larger sheet metal. The cutting is an edge-to-edge cut with a straight bisecting line from one edge to the other. As the top blade moves down and engages the sheet metal placed on the lower surface of the machine.

Equation 4 expresses the cutting force.

$$F_c = L \times t \times S_s \tag{4}$$

Where F_c is the cutting force (N), L is the length of the section to be cut (10 mm), t is the thickness of the sheet metal (0.5 mm) and S_s is the shear strength of the material (320 MPa).

Thus, using a factor of safety of 1.40, the cutting force is calculated as 25.6 kN.

The press force (F_p), applied by the RGS&BPM is expressed as Equation 5.

$$F_p = F_c + F_s \tag{5}$$

WhereF_s is the stripping force (the force required to discharge the cut section from the machine, usually taken as 20% of the cutting force).

Thus, the pressing force is calculated as 25.6 kN.

In addition, the effect of the bending angle on the spring back phenomenon was also investigated. Equation 6 was employed for the calculation of the springback factor (K_s) ().

$$K_s = \frac{\theta_1}{\theta_2} = \frac{\frac{2r_1}{t}+1}{\frac{2r_2}{t}+1} \tag{6}$$

Where: θ_1 is the initial bending angle (degrees), θ_2 is the final bent angle (degrees), r_1 is the initial radius of the component (mm), r_1 is the final radius of the component (mm) and t is the materials thickness (mm).

The final bent angles were measured using a protractor while the radii of the components using a radius gauge.

The thickness of the aluminium sheet metal was 0.5 mm, while the velocity of the guillotine was kept constant at 0.015 mm/sec. A constant cutting force of 25.6 kN and varying bending forces between 5 and 15 kN were employed for the cutting and bending operations for comparative purposes, while the bending angles were made to vary from 30° to 90°.

3. Results and discussion

For the performance evaluation of the reconfigurable guillotine shear and bending press machine, four criteria were used for the evaluation. The first is the investigation of the suitability of the developed machine to carry out the cutting and bending operations successively under pre-determined process conditions. Through direct observation, it was discovered that the machine can perform both operations successively according to the requirements and the pre-determined stated condition at a semi-automatic level.

Secondly, the finish on the edge of the cut materials requires no post-processing by direct observation. By direct observation, the cutting was observed to be smoothly and precisely carried out without any negative impact on the cutting blades. Thirdly, the time taken for the bending and the cutting operations was recorded with the aid of the stopwatch for the replicate experiments, and the average time taken was computed (Table 2). The fourth criterion is the investigation of the springback phenomenon, and the result obtained is presented in Table 3.

Table 2 presents the results obtained for the cutting and bending operations carried out on the aluminium 7075 sheet metal using a cutting force of 25.6 kN and optimum bending force of 10 kN with a punch radius of 2 mm. The experiment was replicated four times for each of the bending angles and the time taken was observed with the aid of a stopwatch. Thereafter, the average bending time taken for each of the bending angles was computed. The bending angles were changed to investigate the effect of the various bending angles on the bending time. The total bending time contributes to the total production time, which in turn determines the manufacturing lead time and the ramp up cost and overall cost-effectiveness of the developed machine.

Figure 5 presents the graphical illustration of the results obtained for the bending operation which indicates the average time taken for the bending operation as a function of the bending and cutting angles. The results show that there is a direct relationship between the average time taken

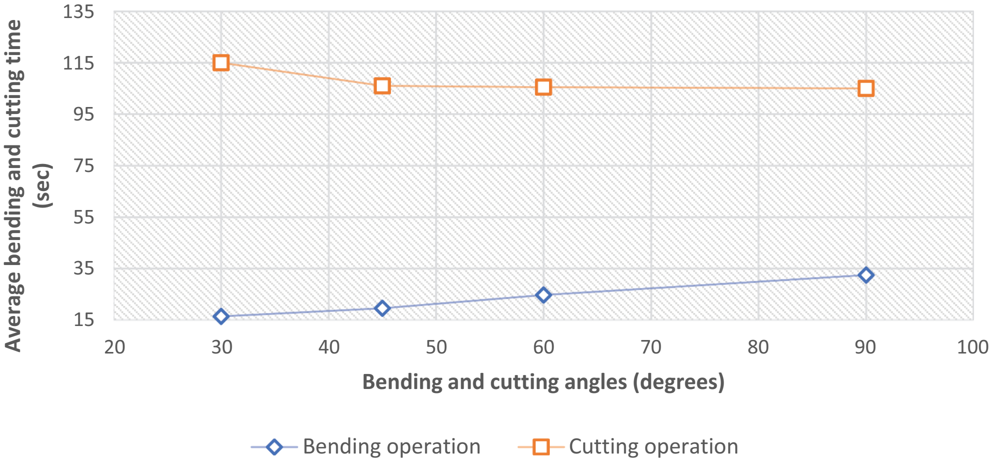
Table 2. Bending and cutting angles with the corresponding time taken for the operations

S/N	Bending and cut angles (degrees)	Average bending time (sec)	Average cutting time at 25 mm back gauge (sec)	Total bending and cutting time for the RGS&BPM (sec)
1.	90	32.49	105	137.49
2.	60	24.74	105.5	130.24
3.	45	19.57	106	125.57
4.	30	16.39	115	131.39

Table 3. The springback factor for bending operations

S/N	Bending angles (degrees)	Bending forces (kN)	Final bent angle (degrees)	Bending radius (mm)	Final bent radius (mm)	Springback factor
1.	90	5	78	2	1.70	1.15
2.	90	10	81	2	1.77	1.11
3.	90	15	80	2	1.75	1.13
4.	60	5	49	2	1.64	1.22
5.	60	10	52	2	1.70	1.15
6.	60	15	51	2	1.69	1.18
7.	45	5	33	2	1.60	1.36
8.	45	10	38	2	1.65	1.18
9.	45	15	36	2	1.63	1.25
10.	30	5	21	2	1.51	1.43
11.	30	10	24	2	1.55	1.25
12.	30	15	23	2	1.54	1.30

Figure 5. Average time taken for the bending and cutting operations.



and the bending angles for the bending operation. The average time taken for the bending operations was observed to increase with an increase in the bending angle.

There are a couple or combination of factors that may cause the time taken for bending operation to increase as the bending angle increases. Prominent among these is the effect of springback or springforward. The springback or springforward phenomenon is a result of the displacement of the molecules as well as the stress and strain induced in the material. It can also be influenced by a combination of factors such as punch radius, nature and specification of tooling, material thickness and yield strength, bending force and angle, bending allowance, as well as the width of the notch of the bottom die (Davoodi and Zareh-Desari., 2014; Fang et al., 2014; Lawanwomg et al., 2014; Lee et al., 2015; Li & Lu., 2015). When a material undergoes bending, the section of the material inside the bending machine fillet undergoes compression with a higher molecular density, while the outside section is stretched with a lower molecular density. The neutral axis remains unaffected. This implies that the dimension of the section of the material inside the bending fillet shortens while the one outside increases. Thus, the compressive forces will be lesser at the outside section than at the inner section, hence, causing the material to return to its original position. The higher the tendency for springback or springfoward as a result of the resistance of the tensile strength of the material to deformation or molecular displacements, the higher may be the time taken for the bending operations. The springback or springforward phenomenon can be compensated by ensuring the right combination of the magnitude, its influencing factors such as punch radius, nature and specification of tooling, material thickness and yield strength, bending force and angle, bending allowance, as well as the width of the notch of the bottom die. For instance, when the values of these influencing factors exceed the optimum, it may trigger the springback or springfoward phenomenon with a reduction in the time effectiveness of the bending operation. Özdin et al., (2014) recommended a combination of a high bending angle and a lower punch radius to tackle the springback or springfroward phenomenon.

Conversely, for the cutting operation, an inverse relationship was observed between the average time taken and the cut angles. The average time taken for the cutting operations was observed to increase with an increase in the cut angle. This result establishes the fact that the bending and cut angles can significantly influence the time effectiveness of the bending and cutting operations.

Table 3 presents the results obtained for the springback phenomenon during the bending operation of the aluminium sheet metal. Springback is a phenomenon whereby a bent sheet metal tries to return to its original shape after bending.

The results presented in Table 3 indicate that the springback phenomenon decreases as the bending angles increase and vice versa. The lowest bending angle (30°) has the highest springback factor of 1.43 under a bending force of 5 kN, while the highest bending angle (90°) has the lowest springback factor of 1.11 under an optimum bending force of 10 kN. This finding agrees significantly with the finding presented by Elsu et al. (2016) during the investigation of the springback behaviour of sheet metal during bending operation. Springback may affect the precision of bending, the shape, conformity and the quality of the final product if not compensated for. The occurrence of springback may be due to the compression of the molecules in the bent component and the stretching of the part molecules outside the bent component. Compressed molecules may try to push themselves apart while the stretched molecules may try to pull themselves back. The alternating pushing and pulling of the molecules after the withdrawal of the bending force may result in a springback. To compensate for the springback phenomenon, there is a need to include a safety factor in the initial bending angles and as such the material is slightly bent beyond the intended angle to give room for springback. Invariably, the springback will bring the material back to the intended angle. However, care must be taken in the selection of the safety factor that will ensure that the springback brings the material to the intended angle. Comparing Tables 2 and 3, it is obvious that there must be a trade-off in the selection of the bending angles. Higher bending angles may promote a reduction in the tendency for springback, thus ensuring high precision in the final angles but with an increase in the time taken for the bending operation. On the other hand, lower bending angles may promote significant time saving for the bending operation but with a tendency for springback which may affect the precision in the final angles. To strike the right balance between the time taken for the bending operation and the precision of bending, there is a need for the optimisation of the process conditions.

Table 3 presents the springback factor for bending operations with varying bending angles (30–90°), varying bending force between 5 and 10 kN and a constant punch radius of 2 mm. The results obtained indicate that under a constant punch radius of 2 mm, the least springback (1.11) was observed under a bending angle of 90° and bending force of 10 kN.

Having established in Table 3 that the optimum bending angle and bending force are 90° and 10 kN, respectively, Figures 6 and 7 visualise the effect of the variation in the bending angles and cutting forces, respectively, on the final bent angles and the springback phenomenon.

Table 4 presents the comparative analysis of the total time taken for the cutting and bending operations carried out on the same material (aluminium 7075 sheet) under the same processing conditions using the developed RGS&BPM vis-à-vis operations using the traditional method of two separate cutting and bending machines. The results indicate that significant time savings can be achieved when both the cutting and bending functions are integrated into one machine rather than carrying them out separately on different machines. From visual observations, it was

Figure 6. The effect of the variation in the bending angles on the final bent angles and the springback.

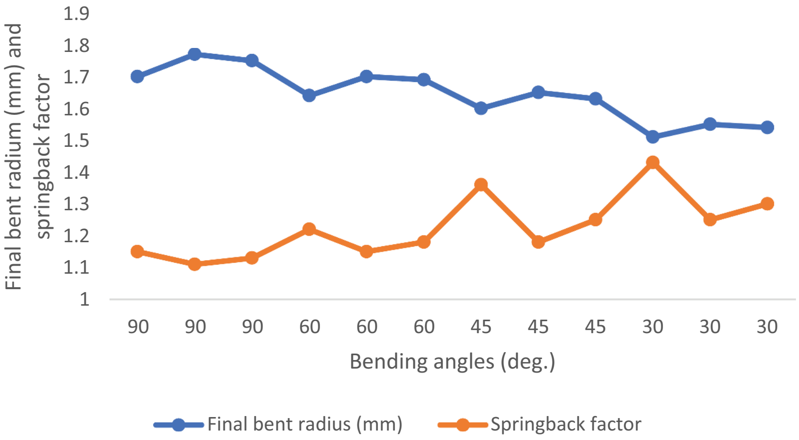


Figure 7. The effect of the variation in the bending forces on the final bent angles and the springback.

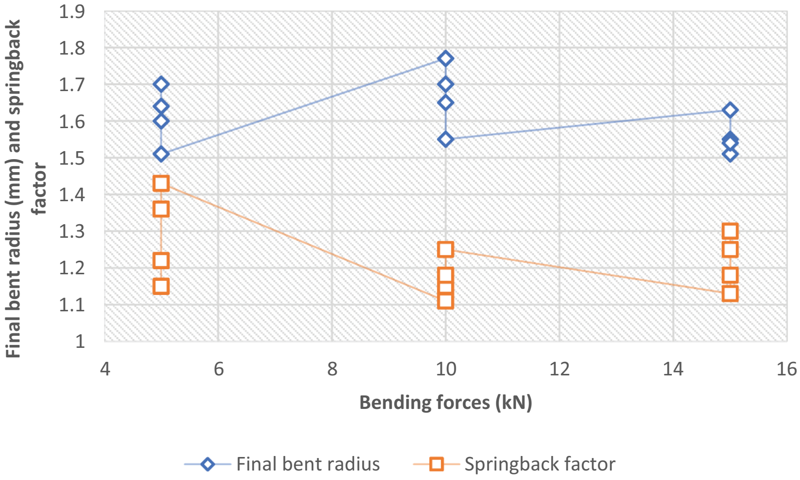


Table 4. Comparative analysis of the total time taken for the cutting and bending operations of the RGS&BPM and the traditional machines

S/N	Bending angles (degrees)	Total bending and cutting time for the RGS&BPM (sec)	Total bending and cutting time for the traditional machines (sec)	% difference
1.	90	137.49	335.67	59.04
2.	60	130.24	324.56	59.87
3.	45	125.57	315.71	60.22
4.	30	131.39	317.89	58.66

discovered that the increase in the time required to complete the cutting and bending operations under the traditional machines (two separate machines) was due to the time required for setting up the machines and the time required to move the components under production from the bending machine to the cutting machine due to the layout of the production shop floor. The percentage difference in the time saved using the RGS&BPM ranges from a minimum value of 58.66% to a maximum value of 60.22%. This implies that the RGS&BPM can eliminate the time it takes to set up different machines for the cutting and bending operations as well as the time required to move component under production between the machines. Over and above that, the two machines require separate storage facilities and material handling equipment.

Table 5 presents the results obtained for the effect of backgauges on the time for the cutting operation. The backgauges are used to ensure that the workpiece is being cut at the exact point

Table 5. Effect of the backgauges on the time for the cutting operation for the RGS&BPM

S/N	Backgauges (mm)	Cutting time (sec)
1.	15	116
2.	20	110
3.	25	96
4.	30	97
5.	35	103
6.	40	104

with precision. Depending on the material being cut, the backgauges may have a different effect on the time for the cutting operation. For the aluminium 7075 sheet evaluated in this study, it was observed that at lower backguages, the cutting time increased but at 25 mm, the cutting time decreased significantly but later increased when increased above 30 mm.

The outcome of the performance evaluation of the developed machine validates some of the principles of reconfiguration such as integrability, convertibility, customisation and diagnosability. The validation of the integrability principle stems from the fact that the machine integrated the components and controls for both the cutting and bending operations. The machine has three modules, two of which can be removed or added to change the machine capacity in terms of length, hence the varying sizes of components that can be worked on. At the time of the experiment, all three modules had been added to the machine and synchronised through the integrability principle, hence all three modules operated as a single machine unit. The components required for both operations were integrated into the machine, while the controls for both components were integrated into one control panel. Both the components and controls were successfully utilised while performing both operations. In other words, the different components and controls were successfully linked together through mechanical, information and control interfaces.

Secondly, for the convertibility principle of reconfiguration, it was observed that the machine possesses the ability to easily switch from an existing functionality such as a bending operation to another (cutting operation). For the customisation principle, the machine is designed around part/product families. Each set of modules provides a different part of the family set, considering that the machine is dual or hybrid. Each module handles a variety of part/product families that are defined by the design dendrogram of the machine work volume envelope, hence it has the flexibility of accommodating a range of part/product families. For the experiment, the machine flexibility was limited to a single workpiece material (aluminium sheet metal) experimented using the full range of the machine.

The diagnosability function is an active safety pin for the machine. For any operation to take place, the diagnosability function sensors detect misalignment, incorrect configuration or reconfiguration, and proper integration of the machine before it can start the operation. In this study, all systems performed perfectly and no malfunction was detected by the diagnosability system, which flags any potential problems and shuts down the machine.

4. Conclusions and recommendations

This study aimed to evaluate the performance of a reconfigurable guillotine machine via physical experimentations. This was achieved by investigating the time taken by the machine for carrying out the bending and cutting operations on aluminium 7075 sheet metal, successively under pre-designed cutting conditions. The effect of the springback phenomenon was also investigated. The thickness of the aluminium sheet metal was 0.5 mm thick, while the velocity of the machine was kept constant at 0.015 mm/sec. A cutting force of 25.6 kN and a varying bending force between 5 and 15 kN were employed throughout the cutting and bending operations, while the bending angles were made to vary from 30° to 90°. The following are the conclusions drawn from the study.

(1) Through direct observation, it was discovered that the machine can perform both the cutting and bending operations successively according to the requirements and the pre-determined stated condition at a semi-automatic level in a time effective manner. The percentage difference in the time saved using the developed machine ranges from a minimum value of 58.66% to a maximum value of 60.22%.

(2) It was also observed that the finish on the edge of the cut materials required no post-processing. By direct observation, the cutting was observed to be smoothly and precisely carried out without any negative impact on the cutting blades.

(3) The results show that there is a direct relationship between the average time taken and the bending angles for the bending operation. Conversely, for the cutting operation, a direct relationship was observed between the average time taken and the cut angles.

(4) The lowest bending angle (30°) has the highest springback factor (1.43), while the highest bending angle (90°) has the lowest springback factor (1.11).

(5) An optimum bending angle of 10 kN produced the least springback (1.11), while the lowest bending force of 5 kN produced the highest springback (1.43).

(6) The results obtained also indicated that higher bending angles promote a reduction in the tendency for springback but with an increase in the time taken for the bending operation. On the other hand, lower bending angles promote significant time saving for the bending operation but with evidence of springback which may affect the precision in the final angles.

This study provides empirical results for the cutting and bending operations of the reconfigurable guillotine shear and bending press machine. It is envisaged that the results obtained from the physical experimentation provide an insight into the effectiveness of the machine in meeting its service and functional requirements. The use of the developed machine can result in considerable time, cost and energy saving thereby promoting the profitability and sustainability of the cutting and bending processes. It is recommended that the machine be subjected to more cutting and bending operations for more performance evaluations. In this study, the performance evaluation was limited to the validation of four reconfiguration principles. These are integrability, convertibility, and customisation diagnosability. Modularity and scalability were not tested as the machine was used with all modules added, without any variation and capacity. To strike the right balance between the time taken for the bending operation and the precision of bending, the optimisation of the process conditions is recommended. Thus, future works can also consider the optimisation of the process parameters to establish the feasible and optimum ranges of the process parameters that are suitable for the cutting and bending operations of aluminium 7075 and other materials. Future work can also validate other reconfiguration principles that were not validated in this study for the developed machine. These include modularity and scalability. Finally, one of the limitations of this study is that the performance evaluation of the developed RGS&BPM was limited to a single workpiece material (aluminium sheet metal) due to the limited availability of materials. Hence, a comparative analysis of the time taken and the occurrence of the springback phenomenon may be carried out for other materials such as stainless and mild steels, etc., of varying specifications such as thickness, length and width among others.

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