PRODUCTION & MANUFACTURING | RESEARCH ARTICLE

Reconfiguration ramp-up cost analysis for a reconfigurable guillotine shear and bending press machine

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Abstract: Reconfiguration is an important manufacturing step that allows the system or the machine to change its function or capacity when introducing a new part family. The purpose of this study is to present a method for determining the reconfiguration ramp-cost for the reconfigurable guillotine shear and bending press machine. To achieve this, the development of reconfiguration ramp-up and costing models was demonstrated. This focuses on the analysis of the ramp-up time and the cost of reconfiguring a dual functional reconfigurable guillotine shear and bending press machine. This includes the conversion of the machine from one function to another and length variation as well as the identification of the ramp-up characteristics and reconfiguration requirements for the machine conversion. From the findings of this study, the conversion cost reduces from $0.3965 during the manual operation to $0.0264 for the automatic operation. This amounts to 93.34% reduction in the conversion cost. In addition, the reconfiguration ramp-up cost reduced from $9.05 for the manual process to $8.68 for the automatic process, which amounts to a 4.08% reduction in the cost. It is expected that the findings of this study will allow manufacturing industries to achieve cost-effectiveness per unit time during reconfiguration operations for improved profitability.

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

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PUBLIC INTEREST STATEMENT

Manufacturing industries strive to shorten the production ramp-up phase to gain a competitive edge and to introduce new products at the shortest possible time. Thus, production ramp-up phase is key to an efficient production system. Therefore industries need to adjust their production systems to achieve a responding manufacturing system. This includes an understanding of the production capacities, process planning, and worker training as vital tools in the management of the production ramp-up phase. This study presents reconfiguration ramp-up cost analysis for a reconfigurable guillotine shear and bending press machine. This is to assist manufacturing industries avoid unnecessary iterative costly routings on the one hand and avails important information that can be analysed to develop effective ramp-up strategies.
Keywords: Reconfigurable machine; Reconfigurable manufacturing system; Ramp-up; Cost; responsiveness; Principles

1. Introduction

Manufacturing is the heart of industrial survival because it is an important process in keeping production companies operational. In reconfigurable manufacturing systems, Manufacturers are constantly searching for ways of improving their business processes to increase productivity (Low et al., 2015). The fast pace inherent in the fast-changing product life cycles requires a new paradigm shift that enables manufacturing systems to respond quickly from the then time-to-market to the new time-to-volume approach, which literally puts the manufacturing systems to full capacity production at the shortest possible time (Terwiesch & Bohn, 2001). In fact, the fast-changing product life cycles that require frequent new product developments that are accompanied by high development costs, are driving designers to cut down the development time (time to market) and the time it takes to reach full capacity utilisation (time to volume; Terwiesch & Bohn, 2001). Frequent changing customer requirements have resulted in shorter product lifecycles which have ultimately increased the frequency of production ramp-ups (Kim et al., 2020). Similarly, preparing a manufacturing system, such as machines, follows on the same trajectory. The turnaround time must be as short as possible. The ultimate result of this scenario means that manufacturers should pay attention to the production ramp-up phase to improve production readiness and productivity. In production ramp-up, three important aspects that must be considered are time to volume, time to market (the product may not be useful until it reaches the market), and time to quality (the product must be of good quality; Johansson & Jensen). They used a ramp-up triangle to show the arrangement. This scenario is depicted in Figure 1.

The bottom of the triangle represents quality, which is an essential prerequisite for customer satisfaction.

Production ramp-up propels an organisation into attaining an improved pay-back time on its production facilities and investment in new product designs (Matta et al., 2007). Production ramp-up, therefore, refers to the period when full product development has been completed and a full production system utilisation commences (Terwiesch et al., 2001). The critical thinking around the ramp-up phase is that initially managers generally have a limited knowledge of the product and process (Fleischer et al., 2003; Scholz-Reiter et al., 2007; Surber et al., 2014). Production systems are very complex systems that need all-round meticulous planning engineered to reduce the time-to-market of new or updated products. The turnaround time involves a complex ramp-up system that is based on physical and logical adjustments which are punctuated largely by trial-and-error decisions (Doltsinis et al., 2013).

Figure 1. The triangle of ramp-up (Johansson & Jensen).
When a new product is introduced, new production lines start or when a new factory is commissioned, production ramp-ups are inevitable (Glock & Grosse, 2015). This shows that there is a direct relationship between a new product and production ramp-up; these two generally occur in sequence (Letmathe and Rößler, 2019). Companies strive to shorten the production ramp-up phase to attract and capture their markets quickly, and introduce new products at the shortest possible time, to become market leaders (Li et al., 2014). As the production ramp-up phase is key to an efficient production system, companies find themselves having to adjust their production systems in various ways to build a responding manufacturing system. This includes an understanding of the production capacities, process planning, and worker training as vital tools in the management of the production ramp-up phase (Kim et al., 2020). The aim of this study is carry out the reconfiguration ramp-up cost analysis for a reconfigurable guillotine shear and bending press machine. The need for this study stems from the fact that ramp-up cost analysis is helpful to engineers to avoid unnecessary iterative costly routings on the one hand and avoids important information that can be analysed to develop effective ramp-up strategies (Doltsinis et al., 2013). **Figure 2** demonstrates a production system ramp-up phase.

### 2. Reconfigurable Manufacturing Systems (RMS) and ramp-up

Reconfigurable manufacturing systems (RMS) provide the best manufacturing environment that responds positively to the constantly changing customer requirements. Responsiveness as defined by Koren et al. (Koren, 2013), is the ability of a system to rapidly add more machines or modules to respond to unexpected changes quickly and economically, to meet the market demand. In reconfigurable machines, reconfiguration is an important step that allows the machine to change its capacity to accommodate a new part family and thus improving productivity. It provides appropriate functionality and capacity at the right time when required (Mittal & Jain, 2014). Capacity change is effected through changeability enablers which apparently include flexibility and reconfigurability (Wiendahl et al., 2007). The time it takes for the system or machines to stabilise after reconfiguration is defined as ramp up (Koren et al., 1999; Mittal & Jain, 2014). The frequent fluctuation in product demand and the variation in product design creates process inadequacies that can be addressed through reconfiguration. Olabanji and Mpofu (Olabanji & Mpofu, 2020) reported that the improvement in design features can
enhance the performance of the reconfigurable machines. Daniyan et al. (Daniyan et al., 2019) developed a reconfigurable fixture for low weight machining operations. The machine demonstrated work adjustable holding capacity during the machining operations of components with low weight. The ramp-up process time considers the period when a manufacturing system or machine has been reconfigured in response to changing targeted manufacturing demands (Malik et al., 2020). Thus, providing appropriate functionality and capacity at the right time when required (Mittal & Jain, 2014). The unpredictable demand by customers, the variety of products and rapid development of new products drive RMS towards a new era where responsiveness period to changing requirements is the key to efficient and cost-effective manufacturing. Hence, the need for the determination of the reconfiguration ramp-up cost for organisations to stay sustainable, productive, and competitive. The sustainability and success of a business require the establishment of these costs to control the variables that may negatively affect the business. To achieve a short cycle of responsiveness, the RMS is designed to be convertible to facilitate the production of new products and be quickly scalable to meet new production capacity requirements (Moghaddam et al., 2018). Figure 3 shows the two stages of a single sheet metal working machine, the first one shown in Figure 3(a) being the standard version and the second being the first stage of the reconfigured machine with increased capacity. Ramp-up, therefore, becomes complete when the machine has been fully reconfigured and ready to function as shown in Figure 3(b).

The RMS is designed with a capability to rapidly change or alter its functional ability to satisfy new system requirements economically (Al-Zaher, 2013). The built-in changeability enabling structure provides up or down scalability and customized flexibility focused on a family of parts that give the system a responsive reconfiguration (Koren & Shpitalni, 2010). For full functionality, the RMS uses a reconfigurable machine tool (RMT) and a reconfigurable controller (Krishna & Jayswal, 2012). The importance of these components is in creating a manufacturing ramp-up approach that puts the system into production with minimum delay. The manufacturing systems require information to facility and enable improved ramp-up (Fjällström et al., 2009). Critical information around the machine
conversion and capacity change play an important role in determining the ramp-up cycle of the system. The RMTs, which are basically modular reconfigurable machines (MRMs), have adjustable and modular structures, Figure 3, which are based on RMS principles (Padayachee & Bright, 2012). The reconfigurable controller, on the other hand, controls RMT functions before and after reconfiguration after receiving commands through the machine graphic user interface. The RMT, like the RMS, is designed around a family of parts where it responds by instituting changes in the hardware and software modules to meet fluctuating market demands (Ashraf & Hasan, 2015). It is the ramp-up time of these modules that must be fully understood to complete the cycle of events in adjusting productivity to match the demand through changed requirements. The RMT is also designed to quickly respond by changing hardware and software modules in response to changes in product designs and demands, for a family of parts the machine is designed to produce (Sibanda et al., 2019). Thus, ramp-up time is very important in RMS systems. It is argued, however, that basing ramp-up on time may not be accurate to measure the system reconfigurability, but the number of components produced give a better representation of the system’s response (Dashchenko, 2006). The cost analysis of reconfiguration ramp-up is very important in manufacturing. It provides an insight into the time and cost wasted during the process of reconfiguration. This will enable the introduction of effective manufacturing ramp up strategies and the determination of the profit-margin between optimised and unoptimised ramp up strategies. Several approaches employed in the evaluation of RMS reconfiguration ramp-up costs. Some researchers consider the cost of installation, the number of units and sensors (Shang et al., 2020) while others consider what they term physical and logical reconfiguration costs (Chen, Zhang, Luo et al., 2009). The essence of these is to capture all the costs and hence reduce the ramp-up time to reduce the costs and optimise production.

To meet production demands, a reconfigurable machine function can be altered through a reconfiguration process and thereafter it should adjust rapidly to the new settings and respond to anticipated production output, thus reducing ramp-up time. Ramp-up time, according to Koren et al. (Koren et al., 1999) as well as Mittal and Jain (Mittal & Jain, 2014), is the period it takes for a newly introduced process setting or just reconfigured production system to stabilise into a steady production sequence in terms of production output and quality, considering the efficiency of the production equipment and labour. There are several approaches employed in the evaluation of RMS reconfiguration costs.

At the machine level, the machine switches from producing one-part family to another. The development of RMTs around a part-family paradigm creates an enabling environment for a cost-effective and mass customised reconfigurable manufacturing environment (Koren & Shpitalni, 2010). Each system of machine reconfiguration, in this era of Industry 4.0, is achieved through the employment of sensors. The diagnostic principle through the sensors monitors the machine
and maintain system configurations that are critical for sustainable operations. Once the machine has been reconfigured and ready to function, true reconfiguration can be guaranteed. The sensors provide the necessary information for the ramp-up cycle process and machine readiness for the task. It is argued that information gathered provides knowledge accumulation and critical in achieving ramp-up time minimisation (Doltsinis & Lohse, 2012). The diagnostic system employs principles of cyber physicals systems which then influences future products as well as the transformation of systems to be more intelligent and resilient to dynamically changing environment (Kao et al., 2015). Cyber physical systems have applications in manufacturing and have led to the introduction of cyber-physical production systems (CPPS) which have direct access to the production equipment information (Pîrvu & Zamfirescu, 2017). Research confirmed that organisations using CPPS enjoy increased efficiency in all production processes and relationships (Nagy et al., 2018). It acknowledged that this results in improved cooperation among specific logistic functions, the market, financial performance, and organisational competitiveness. This can be attributed to the fact that CPPS integrates computation and physical processes using embedded computers and networks to compute, communicate and control the physical process as well as getting feedback in the manufacturing domain (Lee, 2008). The use of the integrability and diagnostic principles of the RMS in the RGS&BPM provide a CPPS compliant platform in the conversion and operation of the machine. For instance, alignment sensors ensure that after a reconfiguration process the modules are properly aligned and the machine correctly synchronised before production. Shown in Figure 4 are alignment sensors embedded in the machine interface.

The conversion process is ensured and scrutinised through sensors that determine the level and accuracy of the conversion process. The diagnostic principle enables the prognosis and diagnosis capabilities of the machine. The research seeks to determine the ramp-up time and cost associated with this reconfiguration process for the reconfigurable guillotine shear and bending press machine (RGS&BPM). Outlined in Figure 5 are applications of the principles of RMS in RMTs.

The principles of RMS explained for RMT (Adapted from Koren et al. (Koren et al., 2018)
2.1. Modularity
Creation of detachable self-contained unit structures of components for the machine 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.

2.2. Scalability
Varying the production capacity of the machine by the addition or subtraction of modules, i.e., modifying the production capacity by adding or removing modules and changing the machine components to scale up or down the machine production capacity.

2.3. Integrability
Rapid and precise integration of modules through control and communication systems. The integral connection and linking of modules or rapidly and precisely integration of modules through mechanical, information, and control interfaces.

2.4. Convertibility
Machine’s ability to easily transform or change existing functionality to suit new production and market requirements. Switches from producing one-part family to another, at machine level and at higher level, adding functions, extending the size of the tool magazine, or expanding the range of the system functionality to produce new parts.

2.5. Diagnosability
After reconfiguration, the RMT must produce quality parts as per requirements. Deviations are identified, and corrective action is taken. It uses control technologies, statistics, and signal processing techniques to achieve this. A machine with a diagnostic function will be able to monitor parts and product quality in real time and identify manufacturing errors or deviations from production planning schedules. This will enable proper troubleshooting of the probable causes of product defects.

2.6. Customisation
Enables the production of a family of parts, or a product family, no single parts. Customised flexibility is possible through dominant features in part families. It takes advantage of group technology.

The principles of RMS play a crucial role in the ramp-up process of the production machine and system. Scalability, is one of the principles which enables integration of the system components by preserving a special space for the addition of more units or machine modules to rapidly increase capacity and thus reduce ramp-up time (Gu & Koren, 2018). According to Chen et al. (Chen, Zhang, Luo et al., 2009), cost-effectiveness is one of the major characteristics of RMS. Ramp-up process time considers the period when a manufacturing system or machine has been reconfigured in response to changing targeted manufacturing demands (Malik et al., 2020). It has been argued that the management of the production system ramp-up phenomenon can be classified into three categories (Matta et al., 2007).

- the analysis and identification of the significant factors affecting the duration of the ramp-up phase and its related costs.
- methods and tools for reducing the duration of the ramp-up phase, and improving the quality of production output.
- tools for aiding the system designer in assessing the system ramp-up during the system configuration/reconfiguration.
These parameters are very vital in developing and understanding the reconfiguration ramp-up costing of reconfigurable machines.

Galan et al. (Galan et al., 2007) presented a methodology for facilitating reconfiguration in manufacturing and many works have been reported on ramp up. For instance, Terwiesch and Bohn (Terwiesch & Bohn, 2001) employed the analytical method to explain the ramp-up with the objective to optimise the yields output ratio at a certain capacity level. Winkler et al. (Winkler et al., 2007) proposed a conceptual model integrated with prognosis tools. The integrated tool is geared towards the management of ramp-up projects. Fleischer et al. (Fleischer et al., 2006) worked on detailed ramp-up simulations for the automotive industry. The simulation was carried out for varying levels of ramp-up maturity in the automotive industry with the aid of capability curves. Ball et al. (Ball et al., 2011) carried out the modelling production ramp-up of engineering products. The study presented a framework through which production ramp-up of engineering products can be modelled. Glock et al. (Glock & Grosse, 2015) presented decision support models for production ramp-up while Low et al. (Low et al., 2015) applied the Lean production principles to facilities design of ramp-up factories. However, specifically the reconfiguration ramp-up cost analysis for a reconfigurable guillotine shear and bending press machine has not been sufficiently highlighted by the existing literature. One of the performance indicators of an RMS highlighted by Pansare et al. (Pansare et al., 2021) is the manufacturing cost. Sustainable manufacturing cost can be achieved through reconfiguration ramp-up cost analysis.

The concept of machine reconfiguration also requires material requirement planning (MRP). This is due to the fact that manufacturing requires the right balance of the production factors and materials is one of them. Effective handling of materials can improve the manufacturing process, productivity, and product quality (Volman et al., 1992). The MRP is a standard supply planning technique for the estimation of the materials required for production and just-in-time delivery. Automated MRP can recognise and connect a production level at which a product appears in the production line to the other. This is to plan for the material required at the next level as well as the estimated arrival time in order to meet the demand of the production line. For a successful operation of MRP, there must be proper accounting for raw materials and inventory at every production level (Gallego, 2022; Volman et al., 1992). In other words, the inventory must be accurate and current, otherwise, it might lead to a wrong input that will produce a wrong output. In the context of a reconfigurable machine, the MRP will provide the estimated materials needed for component production as the machine switches from one configuration to another. The MRP is a function of the nature and amount of the components to be produced, mount of components to be produced, raw materials needed, and the delivery time. A properly executed MRP will reduce the amount of inventory without the risk of material shortage during production, reduce the overall manufacturing time and cost, enhance productivity, product quality, and manufacturing lead time through proper scheduling (Gallego, 2022). For a successful operation of MRP, the determination of the following is required:

- End-product: the component to be produced
- Material plan: the quantity of raw materials needed for manufacturing
- Lot size and quantity: The size and quantity of components to be produced
- Inventory: Material available for use including work-in-progress
- Production plan: including labour, machine type
- Bill of materials: List and cost of all raw materials required to manufacture a component.
Figure 6. Function choice selection.

A detailed MRP will provide information about the task, duration, estimated start time, estimated finish time, personnel assigned, materials needed and their specifications, materials and production flow, quantity, manufacturing stages, production schedules amongst others.

MRP can be executed in the following steps:

- Estimate customers’ demands and materials needed.
- Allocate resources: Compare estimated demand, materials needed with inventory and allocate the manufacturing resources.
- Production scheduling: Determine the amount of time, materials, and labour required at each manufacturing level.
- Monitor: Real-time monitoring to provide alert once there is a delay or deviation.

The fact that the reconfigurable guillotine shear and bending press machine is designed to perform of cutting and bending metal sheets necessitate the analysis of the ramp-up cost. This is to ensure that the operation of the machine is time and cost-effective.

The succeeding sections present the methodology, results and discussion as well as the conclusions and recommendation.

3. Methodology
The reconfigurable guillotine shear and bending press machine (RGS&BPM), designed with dual functionality, can cut and bend metal sheets as a single machine. A prototype of the machine was designed, manufactured, and is currently undergoing tests to evaluate the technology. Based on the six principles of RMS, the machine is modular, scalable, convertibility, integrable, diagnosable and customisable. By virtue of its fully modular nature, the RGS&BPM displays two functions and variable process capacities. This allows it to change functionality and configuration to respond to the wanted function according to available work requirements. The initial stage is determining the process function required in terms of jobs at hand. The machine may be in the cutting or bending function phase, hence the need to recognise the prevailing function and choosing the required one. Shown in Figure 6 are the two functions of the machine and the initial function recognition and selection process.

3.1. The machine conversion process
The conversion process of the RGS&BPM prototype is composed of positional changes of some structural members that are designed to swing up an angle of 135 degrees. This movement creates an opportunity to change the machine functions. Structural members in this case are the bending punch tool holders and the bending punches. Bending and cutting tools are all mounted on the ram simultaneously through tool holders, but on opposite side ends of the ram. The bending punch is designed to be very much longer than the cutting blade, enabling the punch to strategically protrude and hang lower than the cutting blade. This allows the bending punch to interact with the bending die
positioned on the lower ram. The conversion process is conducted manually or automatically. For the bending function or process to be done, the bending punch holder, together with the punch, remain fixed in the vertical position. However, when changing the machine to a cutting function, the punch assembly is swung up an angle of 135 degrees. This creates room for the top cutting blade to slide down past the bottom blade, hence enabling the cutting action. Figure 7 shows the cutting and bending configurations. On the left side, the first module has the bending punch swung 135 degrees up and the cutting blade ready to cut. To the right, the bending punch has been swung down in readiness for bending. In all instances, the cutting blade remains fixed in one position. In the automated option, the swing mechanism is motorised and moves at the touch of a button.

Conversion is part of machine reconfiguration process which is solely responsible for changing the machine function. The other reconfiguration process deals with changing the machine length through adding or subtraction of modules. The reconfiguration process is a manual operation which involves bolting hardware modules together. Sensors are then used to ensure that all modules are properly aligned and secure. As the conversion process is part of the reconfiguration process, the activities are depicted in Figures 8(a and b). At stage 1, the manufacturing processes are identified as bending and cutting. Upon reconfiguration, additional one module was added to stage 2 to obtain three modules at stage 3. The section for each module is shown in Figure 8(b) with the cutting blades.

From Figure 8(b), section 1 is the standard machine configuration without the two module sets depicted as sections 2 and 3. The right-side machine frame is bolted to the right side of section 1 to complete the standard machine structure, and this also happens when modules are added to increase the machine length. Each section comprises all machine components including bending punches, cutting blades, and the combination bottom die/blade unit.
The graphic user interface provides the communication tool used to give instructions to the machine. If the machine is not correctly configured, it cannot perform any function. After a conversion process, say from the cutting function to the bending function, the appropriate light display will be shown, otherwise the machine will park. For the ramp-up process to be
complete, the machine control panel should display the light for the chosen function, if not an alarm will sound and an error signal displayed. Control options are shown in Figure 9.

Each function has sub-functions which are displayed in the graphic user interface for finer details of machine control.

3.2. Reconfiguration ramp-up
As has been established that ramp-up is the process of reconfiguring the machine ramp-up ends when the machine has been fully reconfigured and in a steady production mode. In other words, ramp-up process can be defined as a sequence of changes, variations, and adjustments applied to a system to achieve a desired level of output. Reconfiguration is aimed at providing the necessary system readiness for the desired production needs of the manufacturing process. This comprises changing the machine capacity or functionality to meet the production requirements. The justification for this method stems from the fact that the time it takes to completely reconfigure the
machine defines the efficiency of the reconfiguration process and the cost of ramp-up. For the reconfigurable guillotine shear and bending press machine, reconfiguration is described by two processes, namely, changing the machine length by adding or subtracting modules (scalability) and converting the machine from one function to another (changing the machine from the cutting function to the bending function). As changing the machine configuration means converting the machine from one function to another, it enables a necessary function to be activated and operated. The conversion process can be conducted in two ways, manually or automatically. The general process flow of the events for both manual and automatic conversion processes is depicted in Figure 10 while Figure 11 shows the conversion process reconfiguration. The total time taken to complete the whole reconfiguration process and getting the machine into full production mode can be referred to as ramp-up.
Ramp-up time and cost for the conversion process to activate any one function and changing the machine length in response to the required production parameters will be calculated. The sequence of events is that, first there must be a part or part family of parts to be produced. The machine is then queried using either part features or bend angles (in bending) or part material thickness (in cutting), dimensions, and material type. Also, the function required is outlined so that the machine configuration can be established in relation to the need. The existing machine configuration will then indicate the need for function conversion and/or length change. If there is a need for both, then the time it takes to start the whole process until the machine is ready to start working, the ramp-up time and cost of reconfiguration will then be determined. Figure 12 shows the two functions where in Figure 12(a) the machine is cutting a metal sheet, and then in Figure 12(b) it is bending the metal sheet.

The principles of RMS play a crucial role in the ramp-up process of the production machine and system. For RGS&BPM the ramp-up time can be estimated as Equation 1.

\[
R_t = \sum_{i=1}^{k} \{C_v + R_i, \ldots, R_n\} 
\]  

(1)

where:

\( R_t \) is the total reconfiguration time (secs)

\( C_v \) = conversion process time (sec)

\( R_i, \ldots, R_n \) is the reconfiguration time (sec) for a machine having length from \( i \) to \( n \)

The conversion process time is calculated looking at cutting and bending functions and is expressed as a reversible process as shown in Equation 2.

\[
C_v = C_f \frac{k_1}{k_2} B_f 
\]  

(2)

where:

\( C_v \) is the conversion process

\( C_f \) represents the conversion process to the cutting function

\( B_f \) represents the conversion process to the bending function

\( k_1 \) and \( k_2 \) represent the conversion times from cutting to bending and bending to cutting respectively (sec)

The conversion process is reversible in the sense that if the machine is in the cutting function, it must be converted to the bending function, and similarly, if it is in the bending function mode, it must be converted to the cutting function mode, to perform the requisite functional activities. This is expressed by Equation 3.
Equation 2 is expanded into independent forward and reverse processes that result in Equation 4 formulation.

\[
\frac{dC_f}{dt} = -k_1C_f + k_2B_f; \quad \frac{dB_f}{dt} = k_1C_f - k_2B_f
\]

Length reconfiguration is determined by the number of modules added or subtracted, which is a result of the part production requirement. This is represented by the matrix shown in Equation 5.

\[
R_{ik} = \begin{cases} 
1 & \text{if part } i \text{ is produced in configuration } k \\
0 & \text{otherwise} 
\end{cases}
\]

Where: \( R_{ik} \) is the length reconfiguration

\[ k = n \pm 0 \ldots \ldots 3 \]

\( k = \text{machine configuration while } n \text{ is the number of machine configuration} \)

In manual conversion, a hand is used to move the bending die from position one to position two or vice versa. The window on side of the machine, displayed in Figure 13, facilitates the manual conversion of the machine.

**3.3. Ramp-up time in the conversion process**

The conversion process can be done in two ways, either manually by physically swinging the bending punch holder up an angle of 135 degrees or by using motors to drive the punch holder up 135 degrees. This movement converts the machine from the bending function to the cutting function. The reverse of the indicated process converts the machine back to the bending function. The machine conversion process time can be estimated from the following Equations 6 and 7.
\[ C_{vmt} = C_f^{k_1} B_f^{k_2} \] \hspace{1cm} (6)

Where

- \( C_{vmt} \) is the total manual conversion process time (sec)
- \( C_f \)
- \( B_f \)

The conversion time is given by Equation 7.

\[ C_{cvm} = (u + s_{th} + l)s \] \hspace{1cm} (7)

Where:

- \( u \) is the tool holder unlocking time (sec), \( s_{th} \) is the tool holder swing time (sec),
- \( l \) is the tool holder locking time (sec)

The automatic conversion process uses the same equations. The only difference lies in the completion time taken for each process. In length reconfiguration, several modular components are added or subtracted from the machine to give the desired length. This process is represented by Equation 8.

\[ R_l = \sum_{i=1}^{n} (r_i \ldots r_n) \] \hspace{1cm} (8)

Where:

- \( R_l \) is the length reconfiguration
- \( r_i \ldots r_n = \text{reconfiguration of component } i \text{ on } \)

| Modular Component         | Activity                                      | Estimated Time (mins) |
|---------------------------|-----------------------------------------------|-----------------------|
| Top ram                   | Locate, align, and secure to set torque value | 10                    |
| Bottom ram                | Locate, align, and secure to set torque value | 10                    |
| Motor and actuator unit   | Locate, align and bolt down                   | 10                    |
| Bending punch             | Locate, align, and secure to set torque value | 5                     |
| Cutting blade             | Locate, align, and secure to set torque value | 5                     |
| Bottom die/ blade unit    | Locate, align, and secure to set torque value | 5                     |
| Back gauge unit           | Locate, align, and bolt down                  | 10                    |
| Software                  | Load and Synchronise machine modules          | 5                     |
| **Total time**            |                                               | **60**                |
The total time (t) to add or subtract each component is given by Equation 9.

\[ R_t = \sum_{i=1}^{n} (r_i \cdot t \ldots r_n \cdot t) \]  

(9)

Given in Table 1 are estimated reconfiguration times (illustration example) for critical components.

3.4. Reconfiguration ramp-up costing

In this research, each activity of the reconfiguration process is defined by two models, time, and cost. Time in this context refers to the overall time taken to complete the activity, and cost refers to the monetary value attached to the activity. The reconfiguration \( C_r \) cost calculation is carried out using Equation 10.

\[ C_r = \sum_{i=1}^{n} (r_i \cdot t \ldots r_n \cdot t) \Delta C \]  

(10)

where:

\( \Delta C = \text{machine out of service time} \times \text{machine rate} + \text{total reconfiguration time} \times \text{labour rate} \)

The conversion cost \( C_c \) of the reconfiguration process is calculated from Equation 11.

\[ C_c = C_{cvm} \cdot \Delta C \]  

(11)

The total reconfiguration time that leaves the machine at a steady state for production, that is, the reconfiguration ramp-up cost \( R_{rc} \) is given by Equation 12.

\[ R_{rc} = \sum (C_r + C_c) \]  

(12)

Examples of the reconfiguration and conversion costs calculations are shown in Tables 2 to 4.

The machine comprises of eight (8) components denoted as C1-C8. C1, C2, C3 and C7 and C8 have reconfiguration time of 10 mins each while components C4, C5, C6, and C8 have reconfiguration time of 5 mins. This takes the total reconfiguration time to 60 mins. The machine rate per hour for each of the component, hence, the total machine rate per hour is $24. Furthermore, the labour rate per hour is $5.65 per each component and this takes the total labour rate to $45.2. The total reconfiguration cost was estimated as $8.65.

The abstract values used for illustration of the concepts and the real live production may differ. The values and times used were derived after considering existing standard time values for an artisan working on a machine as given by Company X. Two approaches used in the calculation were based on automatic and manual reconfiguration, specifically, for the conversion process. Length reconfiguration is purely manual. In manual reconfiguration, the time is longer due to the movement of the person in changing the machine configuration. The speed of operation, though standard times may give an average time, depends entirely on the efficiency of the individual. For this work, however, times based on information provided by Company X.

For automatic conversion, the values used were based on human machine interaction. The time it takes to press a button and the time it takes for the motors to respond to the given command.
After observing that scenario and the response time of the motors, as per design of the control system, an average time was deduced for this analysis.

The analysis indicates that the greatest time is lost in the length adjustment process, which controls the entire reconfiguration process. The indication is that there is a need to improve or further develop a better length reconfiguration process to control the ramp-up cost and improve productivity.

For this study, the reconfiguration cost excludes other types of cost such as the installation, production, machine assembly or disassembly costs etc. The emphasis is on the time it takes the machine to switch from one manufacturing activity to another and this was estimated both on the manual and automatic basis for comparative analysis. Hence, only the running cost was considered for exact estimate of the reconfiguration time (The time it takes the machine to change from one activity to another). The time component of the reconfiguration process is then converted to cost using the machine and labour rates in order to determine the cost-effectiveness of the reconfiguration process.

| Table 2. Reconfiguration cost calculation |
|------------------------------------------|
| Component No. | Reconfiguration Time (mins) | Machine Rate ($/h) | Labour rate ($/h) | Reconfiguration Cost ($) |
|---------------|-----------------------------|--------------------|-------------------|-------------------------|
| C1            | 10                          | 3                  | 5.65              | 1.4417                  |
| C2            | 10                          | 3                  | 5.65              | 1.4417                  |
| C3            | 10                          | 3                  | 5.65              | 1.4417                  |
| C4            | 5                           | 3                  | 5.65              | 0.7208                  |
| C5            | 5                           | 3                  | 5.65              | 0.7208                  |
| C6            | 5                           | 3                  | 5.65              | 0.7208                  |
| C7            | 10                          | 3                  | 5.65              | 1.4417                  |
| C8            | 5                           | 3                  | 5.65              | 0.7208                  |
| Total         | 60                          | 24                 | 45.2              | 8.65                    |

| Table 3. Manual conversion process cost |
|-----------------------------------------|
| Activity | Time (Secs) | Time (h) | Machine rate ($/h) | Labour rate ($/h) | Conversion Cost ($) |
|-----------|-------------|----------|-------------------|-------------------|-------------------|
| Unlock    | 60          | 0.0166   | 3                 | 5.65              | 0.1442            |
| Swing     | 45          | 0.0125   | 3                 | 5.65              | 0.1081            |
| Lock      | 60          | 0.0166   | 3                 | 5.65              | 0.1442            |
| Total     | 165         | 0.0457   | 9                 | 16.95             | 0.3965            |

| Table 4. Automatic conversion process cost |
|--------------------------------------------|
| Activity | Time (Secs) | Machine rate ($/h) | Labour rate ($/h) | Conversion Cost ($) |
|----------|-------------|-------------------|-------------------|-------------------|
| Unlock   | 0.5         | 3                 | 5.65              | 0.0012            |
| Swing    | 10          | 3                 | 5.65              | 0.0240            |
| Lock     | 0.5         | 3                 | 5.65              | 0.0012            |
| Total    | 11          | 9                 | 16.95             | 0.0264            |
An important consideration in the ramp cost analysis is the fact that when a product configuration changes, the assembly sequence of operations for the new product also changes. Hence, the determination of an appropriate sequence of assembly operations will further minimize the number of assembly stages without any inference. This will promote time and cost-effectiveness during assembly operations (Bahubalendruni, Gulivindala, Kumar et al., 2019; Bahubalendruni, Gulivindala, Varupala et al., 2019).

4. Results and discussion

In Tables 2 and 3, a comparative analysis of the manual and automatic machine conversion process time and costs were carried out. The machine rate is the cost of running the machine for a specified time. The results obtained indicated that for three activities, namely: “unlock” “swing” and “lock” in the manual conversion mode, the total conversion time was 165 sec, at a machine rate of $9, labour rate of $16.95 per hour. This takes the total conversion cost to $0.3965. Conversely, for the automatic conversion mode, with the total conversion time reduced to 9 sec. Using the same machine rate ($9), labour rate of ($16.95) per hour, the total conversion cost to $0.0264. This amounts to 93.34% reduction in the conversion cost. This implies that the automatic mode is more cost and time effective compared to the manual mode. The variation in the time for the three activities in Tables 3 and 4 is due to certain factors such as task complexity, reachability, visibility, navigation, and possible ergonomic considerations as it relates to man and the machine etc.

Table 3 demonstrates the calculation of the manual machine conversion process cost.

Table 4 shows an automatic conversion process cost.

The overall reconfiguration ramp-up cost can then be obtained using Equation 13.

\[ R_{rc} = \sum (C_r + C_c) \]  \hspace{1cm} (13)

\[ R_{rc} = \sum (8.65 + 0.3965) \text{ or } R_{rc} = \sum (8.65 + 0.0264) \]

\[ R_{rc} = $9.05 \text{(manual conversion)} \text{ or,} \]

\[ R_{rc} = $8.68 \text{(automatic conversion)} \]

Figure 14. Comparison of the manual and automatic machine conversion process time.
The reconfiguration ramp-up cost reduced from $9.05 for the manual process to $8.68 for the automatic process, which amounts to a 4.08% reduction in the cost.

The time and cost-effectiveness of the automatic conversion compared to the manual conversion is depicted in Figures 14 and 15.

The reconfiguration times are normally based on standard times for the operation. However, the actual times maybe based on the staff competency and technological advances in the organisation. More features maybe added such as machine loading and setup times but for this paper these are not considered as part of reconfiguration and ramp-up costing.

The analysis indicates that the greatest time is lost in the length adjustment process, which controls the entire reconfiguration process. The indication is that there is a need to improve or further develop a better length reconfiguration process to control the ramp-up cost and improve productivity.

5. Practical implications
The ramp-up model seeks to reduce the time lost in the process, which ultimately means improved ramp-up equates to reduced costs of production. The complexity of the reconfiguration ramp-up costing is based on the components that make up the production ramp-up process. Automated reconfigurable processes or machines may achieve a better ramp-up period as indicated in the calculated costs of the reconfiguration ramp-up process. As ramp-up is a phase where the manufacturing capacities and capabilities are altered in response to new manufacturing dictates, it is an inevitable manufacturing process; hence, it should be critically analysed to reduce the cost of production. A delayed process or a prolonged process has cost implications on the production process and part/product cost. This study gives an example of the calculation of reconfiguration ramp-up costing for the machine.

Production parameters, manufacturing requirements, and available technologies, determine the ramp-up and cost management efforts for the system. The importance of determining the reconfiguration ramp-up cost lie in the cost of product manufacturing. The sustainability and success of
a business require the establishment of these costs to control the variables that may negatively affect the business. Globally, the competing market forces driving survival of businesses and products, demand an improved manufacturing environment that can offer increased responsiveness, flexibility, and reliability of the manufacturing units. Well organised and synchronised manufacturing units that respond timely to the customer needs have a sure case of survival. Thus, reconfigurable manufacturing systems and machines have the potential to satisfy these needs. Reconfiguration ramp-up costs analysis is very vital in ensuring that the system provides the necessary response right from the outset. A properly reconfigured system that timely responds to market demands ensures a cost-efficient and sustainable manufacturing environment. The importance of such an approach helps in bringing to perspective the actual drivers of costs in both the reconfiguration and ramp-up time of the process. This influences the management of the manufacturing ramp-up phase in an organisation. It also influences managerial decision about the selection of the most effective ramp-up strategy that boast of time and cost-effectiveness. This is will also assist manufacturers to achieve manufacturing cost sustainability in order to keep the business competitive. From the research perspectives, there is a need to perform more performance evaluation to validate the reconfiguration ramp-up cost with physical experimentations. This is due to the fact that the study is limited to abstract values for the illustration of the concepts and the real live production may differ.

6. Conclusion
The purpose of this research was to present a method for determining the reconfiguration ramp-cost for the reconfigurable guillotine shear and bending press machine. A method of conducting the calculations was formulated and an example used to demonstrate the components used in the determination of the ramp-up cost. The development of reconfiguration ramp-up and costing models has been demonstrated in the paper. Reconfigurations ramp up cost is one of the most important attributes that characterize the efficiency of RMS. In this paper, a model of the approach was demonstrated for a reconfigurable guillotine shear and bending press machine. The machine follows the RMS principles and provides a responsive approach to customer demands. The paper underpins an important consideration for the cost of reconfiguration as a reversible process that ramps in the machine conversion as part of the reconfiguration process. From the findings of this study, the conversion cost reduces from $0.3965 during the manual operation to $0.0264 for the automatic operation. This amounts to 93.34% reduction in the conversion cost. In addition, the reconfiguration ramp-up cost reduced from $9.05 for the manual process to $8.68 for the automatic process, which amounts to a 4.08% reduction in the cost. It is expected that the findings of this study will allow manufacturing industries to reduce the cost per unit time during reconfiguration operations for improved profitability.

Further analysis is set be conducted on the machine as it gets subjected to live tests.

Acknowledgements
The authors are very grateful to the National Research Foundation (NRF), Gibela Rail Consortium, and the Industrial Engineering Department at Tshwane University of Technology (TUT) for providing relentless support during the research, any opinion, findings, recommendations, and conclusion expressed in this material is that of the authors. NRF, Gibela, and TUT have no liability in this regard.

Funding
The authors disclosed receipt of the following financial support for the research: Technology Innovation Agency (TIA) South Africa, Gibela Rail Transport Consortium (GRTC), National Research Foundation (NRF grant 123575) and the Tshwane University of Technology (TUT).

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Disclosure statement
No potential conflict of interest was reported by the author(s).

Citation information
Cite this article as: Reconfiguration ramp-up cost analysis for a reconfigurable guillotine shear and bending press machine, Vernan Sibanda, Khumbulani Mpofu, Ilesanmi Danyion & Felix Ale, Cogent Engineering (2022), 9: 2085002.
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