Journal of Physics:
Conference Series

PURPOSE-LED
PUBLISHING™

PAPER • OPEN ACCESS

On the use of Process Work as an Indicator for Process Disturbance in industrial Sheet Metal Forming

To cite this article: Alexander Barlo *et al* 2025 *J. Phys.: Conf. Ser.* **3104** 012103

NUMISHEET-2025 IOP Publishing
Journal of Physics: Conference Series **3104** (2025) 012103 doi:10.1088/1742-6596/3104/1/012103

On the use of Process Work as an Indicator for Process Disturbance in industrial Sheet Metal Forming

Alexander Barlo[1,*], **Martin Nitsche**[2], **Mats Sigvant**[1,3] **& Johan Pilthammar**[1,4]
[1]Blekinge Institute of Technology, Karlskrona, Sweden
[2]AutoForm Engineering GmbH, Berlin, Germany
[3]AutoForm Engineering AB Sweden, Olofström, Sweden
[4]Volvo Cars, Dept. 81153 Concept Engineering, Olofström, Sweden

E-mail: `Alexander.Barlo@bth.se`

Abstract. This study explores the estimation of process work in the sheet metal forming process by numerically integrating the punch force curve as a function of the press crank angle. Two numerical integration methods, the trapezoidal rule and Simpson's 3/8 rule, are evaluated for their ability to estimate process work. While both methods yielded similar results, the Simpson 3/8 rule was found to produce significantly lower estimation errors. The method was then tested in an industrial case study involving the production of Volvo XC90 front door inner components. By analyzing the process work for each blank, it was found that the method effectively captured changes in applied cushion force and material coil. A further analysis, incorporating average lubrication data, showed that the process work also accurately reflected variations in lubrication conditions. The results suggest that process work could serve as a cost-effective and efficient tool for in-line monitoring of process health and has the potential to improve process monitoring and quality control in industrial sheet metal forming operations.

1. Introduction

In pursuit of more efficient and accurate manufacturing processes, an increasing amount of sensor data is being utilized to enable data-driven decision-making. This aligns with the principles of Industry 4.0, where the concept of Zero Defect Manufacturing (ZDM) can be advanced through key enabling technologies such as Big Data analytics, inspection and monitoring, Cyber-Physical Systems (CPS), and Artificial Intelligence (AI) [1, 2]. However, implementing and retrofitting sensors for data collection across an entire production line or facility is a costly endeavor. Beyond the substantial investment in sensors, the challenge of managing large volumes of data arises, as existing equipment is often inadequate for this purpose [3]. Consequently, developing new methodologies for process monitoring and control using existing data collection infrastructure is of significant industrial interest.

In the automotive industry, sheet metal forming is a widely used process for manufacturing body components. This is a relatively high-speed process, with throughput rates ranging from 8 to 20 components per minute, depending on the component geometry and the layout of the press line. A forthcoming challenge for the industry is the introduction of recycled material

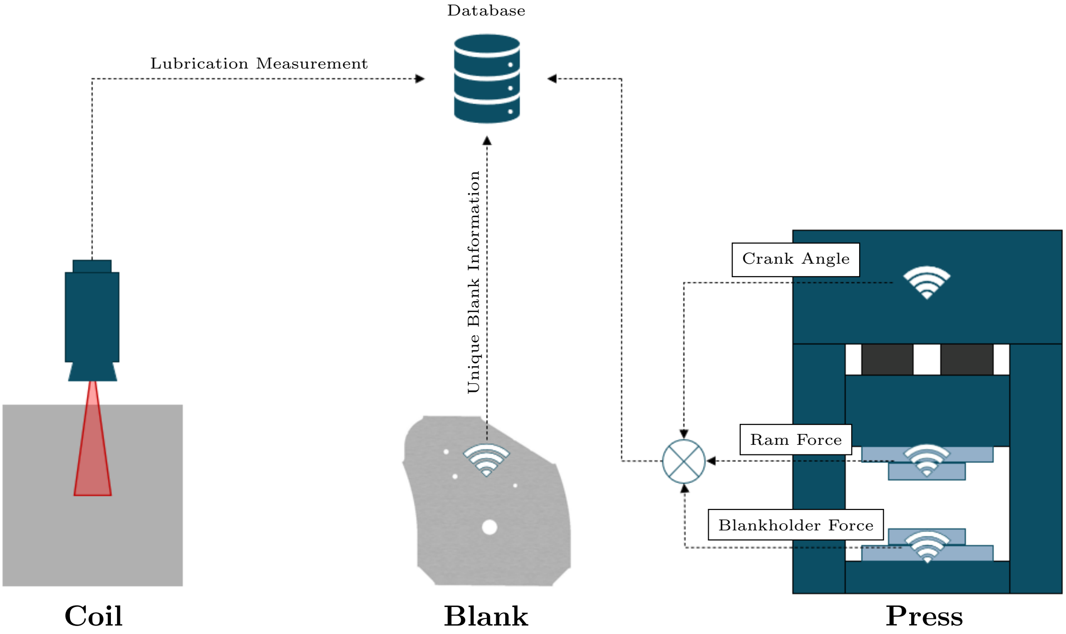


Figure 1. Data acquisition in the production of the Volvo XC90 front door inner component.

grades [4]. These materials are expected to exhibit greater variability in mechanical properties than currently observed, raising concerns about in-coil variations. To address these challenges, leveraging data-driven solutions presents a promising strategy [5, 6].

A recent study by Liu et al. [7] describes data extracted from metal forming processes as "information absent" and "fragmented." At the Volvo Cars Stamping Plant in Olofström, Sweden, efforts have been made to develop advanced process monitoring approaches by integrating both existing and newly acquired sensor data. These efforts aim to address the concerns raised by [7] by consolidating large quantities of data into a single database. One specific component selected for investigation is the Volvo XC90 Front Door Inner, chosen due to its relatively large size and draw depth.

Data for this component is collected at three key locations along the production flow. In the blanking line, a laser sensor measures the lubrication levels on the coil with an acquisition rate of approximately 17 [Hz], and correlates each blank's position and stack to a specific location on the coil. In the press, continuous data are recorded, with an acquisition rate of approximately 52 [Hz], relating to press forces and the crank angle. The press forces recorded are the cushion and ram forces, with the cushion force being calculated based on the hydraulic pressure in the cylinders under the cushion, while the ram force is measured by strain gauges in each connecting rod. For the recording of the crank angle, this parameter is measured directly on the main crank of the press. A schematic illustrating the sensor placements and data flow is presented in Figure 1.

This study will investigate how the collected data can be utilized for process monitoring by calculating the mechanical work exerted by the press based on the press punch force. This calculation will be performed using numerical integration, and the results will be compared against known process variations and lubrication data to assess the validity of the proposed method.

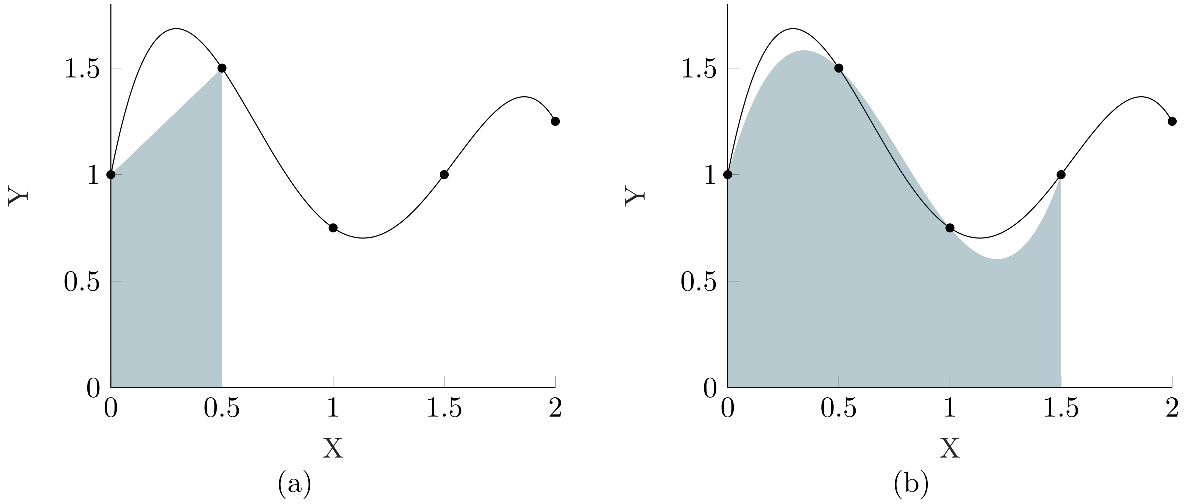


Figure 2. Visualization of numerical integration steps for (a) the trapezoidal rule, and (b) Simpson's 3/8 rule.

2. Numerical Integration

For the numerical integration of the force curve, two different methods are investigated: the trapezoidal rule and Simpson's 3/8 rule. The trapezoidal rule is the simplest numerical integration method, approximating the integral using piecewise linear segments [8, 9]. This method has an accuracy of $\mathcal{O}(h^2)$ and is illustrated in Figure 2(a). In contrast, Simpson's 3/8 rule is a more advanced technique that employs piecewise cubic interpolation [8, 9], offering a higher accuracy of $\mathcal{O}(h^4)$, as illustrated in Figure 2(b).

2.1. Data Type and Area of Interest

From the measurement system outlined in Figure 1, the press line provides data on ram force, cushion force, and crank angle. An example of the ram force and cushion force as functions of the crank angle ($F_r(\varphi)$ and $F_c(\varphi)$ respectively) is presented in Figure 3(a). To determine the process work, the evolution of the punch force over the stroke is of primary interest. This can be calculated as follows:

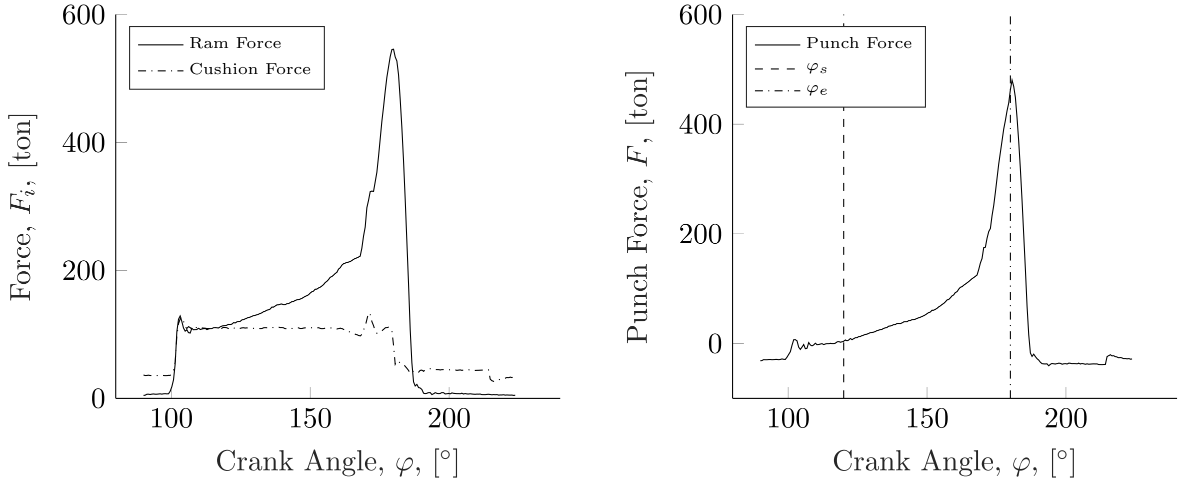
$$F(\varphi) = F_r(\varphi) - F_c(\varphi) \tag{1}$$

and is exemplified in Figure 3(b). The punch force is of particular interest in determining the process work, as observations indicate that it remains a consistent force throughout the process.

The press measurements cover the entire stroke, with crank angles in the range $\varphi \in \{90°, 90.6°, \dots, 223.8°\}$. However, the full range is not required for determining the process work, necessitating the selection of starting (φ_s) and ending (φ_e) values for numerical calculations.

As observed in Figure 3(b), a significant positive punch force is not reached until approximately 120° which is therefore chosen as the starting value φ_s. Ideally, the evaluation would extend to bottom dead center (BDC), where the punch force typically reaches its maximum. However, in real-world production environments, process conditions vary, making it impractical to rely on a single, fixed crank angle for the location of the maximum punch force. To ensure consistent and comparable evaluations across all strokes, the analysis is terminated at 180°, which is close to BDC.

Thus, the evaluation is conducted over the range $\varphi \in \{120.0°, 180.0°\}$, as illustrated in Figure 3(b).



(a) (b)

Figure 3. Example of measured ram and cushion force signals (a) and calculated punch force (b)

2.2. Trapezoidal Rule

As previously mentioned, the trapezoidal rule for numerical integration is the simplest method, assuming a piecewise linear approximation [8]. The area under the force curve can thus be determined as:

$$W_p = \int_{\varphi_s}^{\varphi_e} F(\varphi)\, d\varphi \quad \approx \quad \sum_{i=1}^{N} \frac{F(\varphi_{i-1}) + F(\varphi_i)}{2} \Delta\varphi_i \tag{2}$$

where $F(\varphi)$ is the measured punch force as a function of the press crank angle, and the limits φ_s and φ_e represent the crank angle at the predetermined angle space, so $\varphi \in \{120°, 180°\}$.

To evaluate the accuracy of the piecewise linear approximation, the error for each trapezoidal panel (e_i) can be estimated. The sum of the absolute errors across all panels provides a comparable measure of the overall error:

$$E = \sum_{i=1}^{N} |e_i| \qquad \text{where} \qquad e_i = -\frac{(\varphi_i - \varphi_{i-1})^3}{12} \cdot F''(\varphi_c) \tag{3}$$

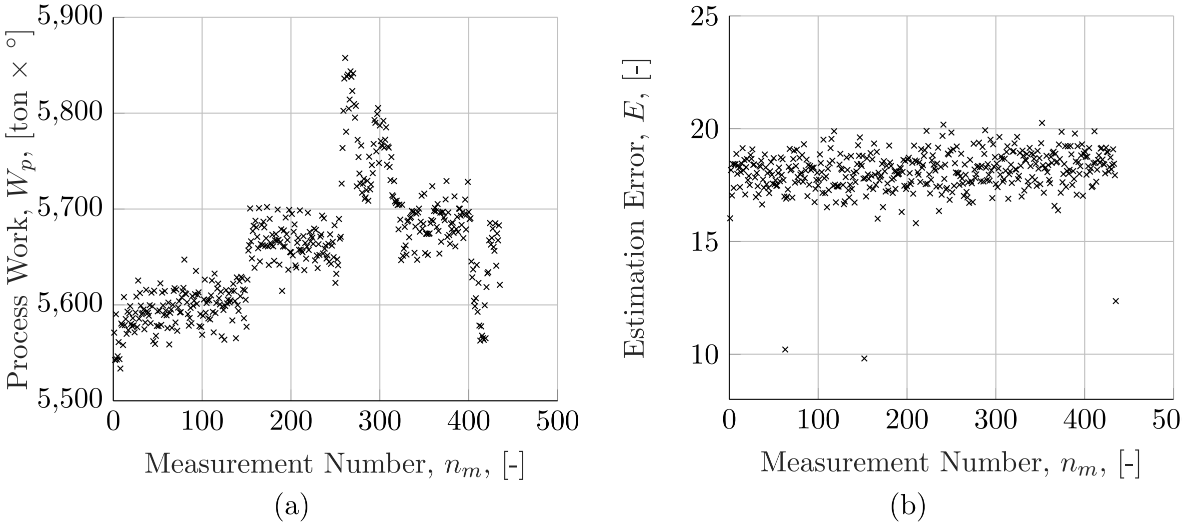
For the calculation of the error for each individual panel (e_i), φ_i and φ_{i-1} represents the endpoints of the panel, while $F''(\varphi_c)$ denotes the second derivative of the function at some unknown point $\varphi_c \in \{\varphi_{i-1}, \varphi_i\}$. Since $F''(\varphi_c)$ is generally unknown, it is approximated numerically for each panel using the Finite Difference Method (FDM).

Applying Eq. 2 to a subset of recorded production data (obtained from the system outlined in Figure 1), the process work shown in Figure 4(a) is calculated, with the corresponding accumulated estimation error presented in Figure 4(b).

2.3. Simpson 3/8 Rule

The Simpson 3/8 rule offers an alternative method for numerical integration. In contrast to the trapezoidal rule, this method assumes a piecewise cubic approximation [8]. The area under the force curve can, therefore, be determined using this method as follows:

$$W_p = \int_{\varphi_s}^{\varphi_e} F(\varphi)\, d\varphi \quad \approx \quad \sum_{i=1}^{N} \frac{F(\varphi_i) + 3F(\varphi_{i+1}) + 3F(\varphi_{i+2}) + F(\varphi_{i+3})}{8} 3h \tag{4}$$



(a) (b)

Figure 4. Process work (a) and estimation error (b) of a subset of measurements using the trapezoidal rule.

where h represents the step size and is defined as:

$$h = \frac{\varphi_{i+3} - \varphi_i}{3} \tag{5}$$

For error estimation, an approach similar to that used for the trapezoidal rule is employed. The accumulated error of the Simpson 3/8 method is defined as:

$$E = \sum_{i=1}^{N} |e_i| \qquad \text{where} \qquad e_i = -\frac{(\varphi_{i+3} - \varphi_i)^5}{6480} \cdot F''''(\varphi_c) \approx -\frac{(\varphi_{i+3} - \varphi_i)^5}{6480} \cdot F''(\varphi_c) \tag{6}$$

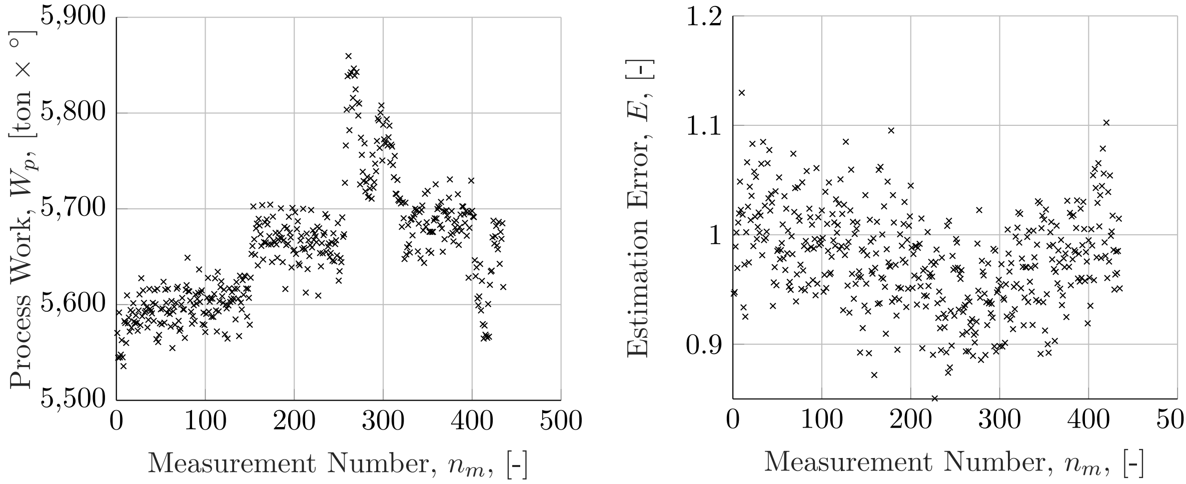
where $F''''(\varphi_c)$ is the fourth derivative of the function at some unknown point $\varphi_c \in \{\varphi_i, \varphi_{i+3}\}$. To simplify the estimation of the error, the fourth derivative $F''''(\varphi_c)$ can be approximated by the second order derivative $F''(\varphi_c)$ [8, 9] allowing for a numerical approximation using FDM.

Applying Eq. 4 to the same subset of recorded production data used for the trapezoidal rule, the process work and the accumulated estimation error, shown in Figures 5(a) and (b), respectively, are obtained.

2.4. Comparison

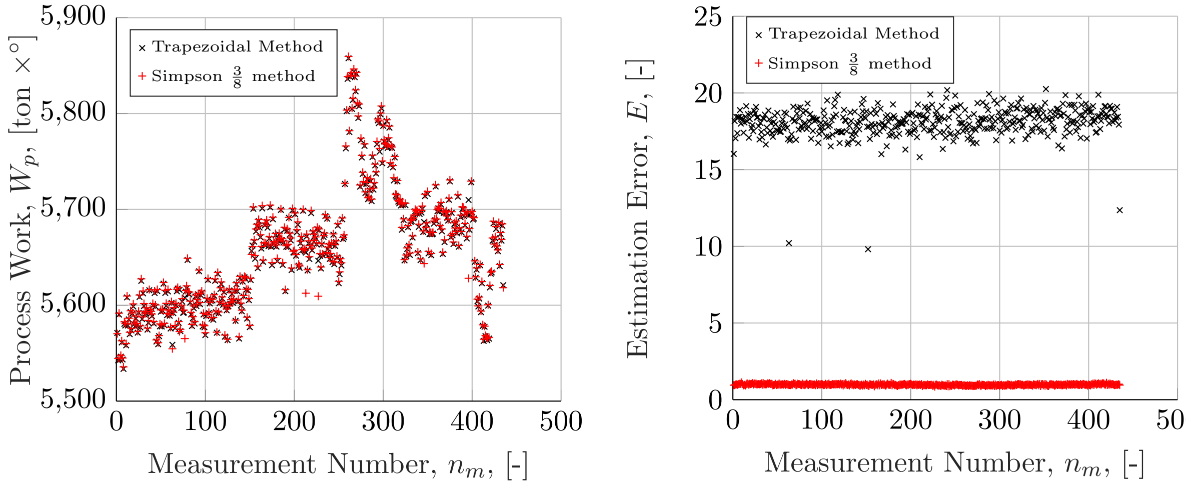
A comparison between the trapezoidal and Simpson 3/8 rules reveals that the estimated process work is highly similar for both methods. This comparison is shown in Figure 6(a). The difference in accuracy between the two methods becomes evident when examining the accumulated estimation error, presented in Figure 6(b). The estimation error for the trapezoidal rule, with a mean value of 18.1, is significantly higher than that of the Simpson 3/8 rule, which has a mean value of 0.978.

In this case, the force signal does not appear to be highly sensitive to the choice of numerical integration rule, as only minor deviations are observed in the estimated process work values. However, upon examining the accumulated estimation error, it is evident that the Simpson 3/8 rule provides the most accurate estimation of the actual work. Therefore, this method will be employed for numerical integration in the industrial use case presented in this study.



(a) (b)

Figure 5. Process work (a) and estimation error (b) of a subset of measurements using the Simpson 3/8 rule.



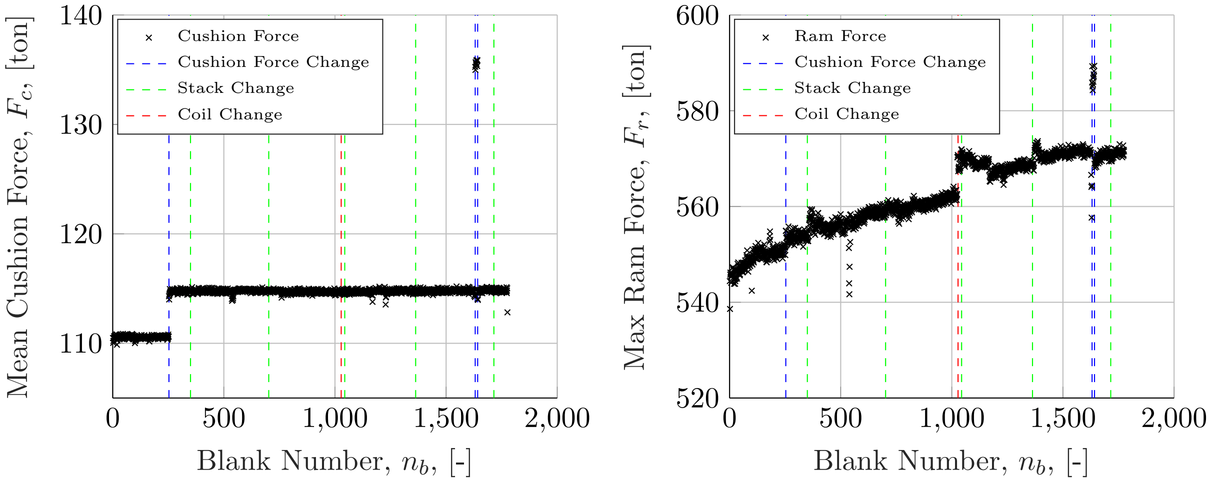
(a) (b)

Figure 6. Comparison of the Trapezoid and Simpson 3/8 rule showing (a) the calculated process work, and (b) the accumulated estimation error.

3. Industrial Use Case

To test the proposed method in an industrial setting, a batch of Volvo XC90 front door inner components was monitored. Figures 7(a) and (b) present the measured mean cushion force and maximum ram force values, respectively. During the batch, changes in cushion force, stacks, and coils were recorded. These changes are shown in Figures 7(a) and (b).

Using Eq. 4, the process work for all stamped components is calculated. The results are presented in Figure 8, along with the changes in process conditions. Based on the known variations in process conditions, an initial evaluation of the method can be made. Approximately 250 blanks into the batch, an active change was implemented in the cushion force, increasing it from 110 to 115 tons. Between blanks 1630 and 1640, a test was conducted in which the cushion force was briefly raised to 135 tons before being lowered back to 115 tons. Figure 8 clearly shows



(a) (b)

Figure 7. Mean cushion force (a) and maximum ram force (b) obtained during the industrial trail. Both figures show recorded changes in cushion force, stack changes in production, and a coil change within the stacks.

Coil #	$\mathbf{R_{p,02}}$**[MPa]**	$\mathbf{R_m}$ **[MPa]**	**r [-]**	**Zn (Upper) [g/m^2]**	**Zn (Lower) [g/m^2]**
# 1	157	291	2.25	41.0	41.0
# 2	163	301	2.40	43.0	41.0

Table 1. Supplier provided material certificate data for the two coils of VDA239-100 CR4 mild steel used in the batch.

that the calculated process work responds immediately to these cushion force changes.

Regarding the stack changes during the process, it can be observed in Figure 8 that the process work exhibits either a smaller or larger change whenever a stack change occurs. However, based on the process work alone, it is not possible to determine the exact cause of the change at the time of stack alterations; nonetheless, it provides valuable insight into the process status. The process work is particularly informative when a coil change occurs, such as around 1050 blanks into the batch. Here, an abrupt shift in the overall level of the process work is observed. This change can be attributed to the fact that the material in coil #2 is stronger than that in coil #1. Material and coating details from the material supplier certificate data are provided in Table 1.

An interesting aspect of the process work determined for the batch is that it appears to capture the temperature ramp-up in the tools. At the beginning of the batch (from blank 1 to approximately 100), a steady increase in work is observed. Similar trends can be seen starting around blank 550 and 1150. This progression in the process work is believed to be caused by the thermal impact on the tribological system. A previous study by Barlo et al. [10] demonstrated through numerical analysis how a similar component can transition from a safe to a failed part due to temperature-induced changes alone.

Some fluctuations in the process work cannot be explained by the observed changes in cushion force, stack, or coil. Notably, a sudden and brief peak in process work occurs between blanks 800 and 875. This peak is believed to result from a sudden change in lubrication conditions on the blanks. To investigate this change in process work, the lubrication data obtained from the Volvo Cars DAQ system (as illustrated in Figure 1) is analyzed. The lubrication amount is measured using a crosshead laser sensor, producing a sensor signal similar to the one shown in Figure 9(a). In the coil, migration of the lubrication is observed, with a higher lubrication

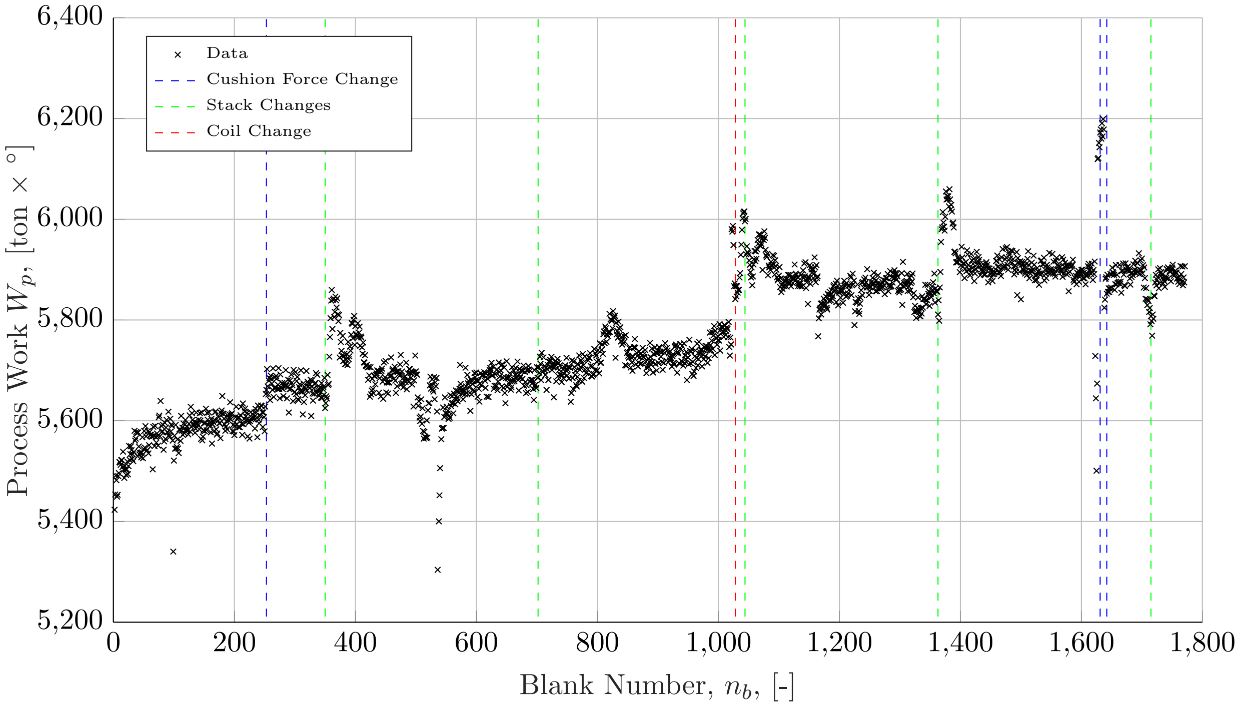
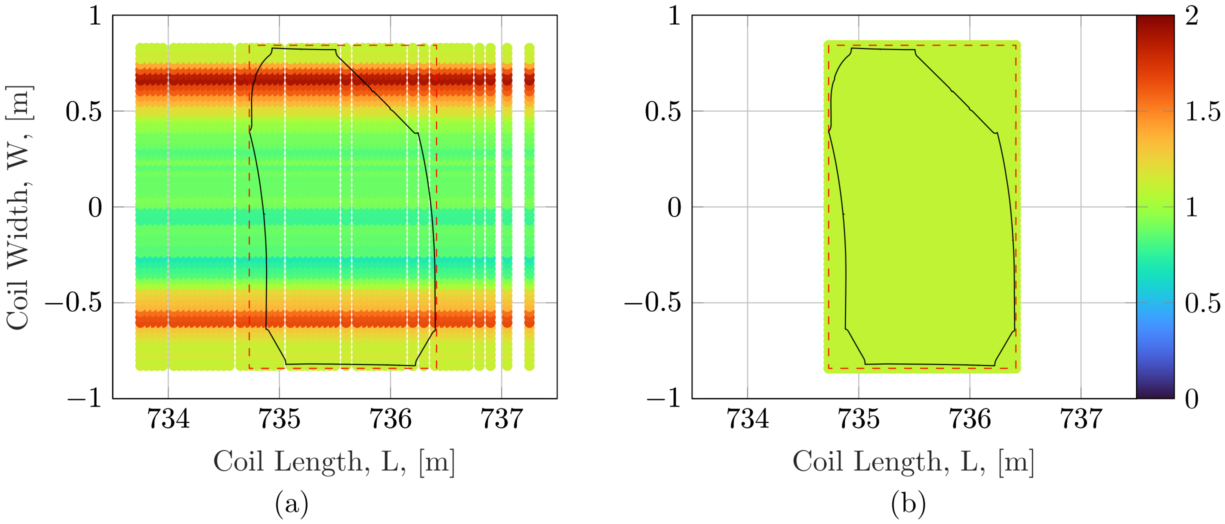


Figure 8. Process work determined for each blank in a full production batch of the Volvo XC90 front door inner component.



(a)

(b)

Figure 9. Examples of (a) as-measured lubrication distribution (ϱ) in [g/m^2] on the bottom of the coil for a single blank, and (b) estimated average lubrication ($\bar{\varrho}$) in [g/m^2] for the blank bounding box.

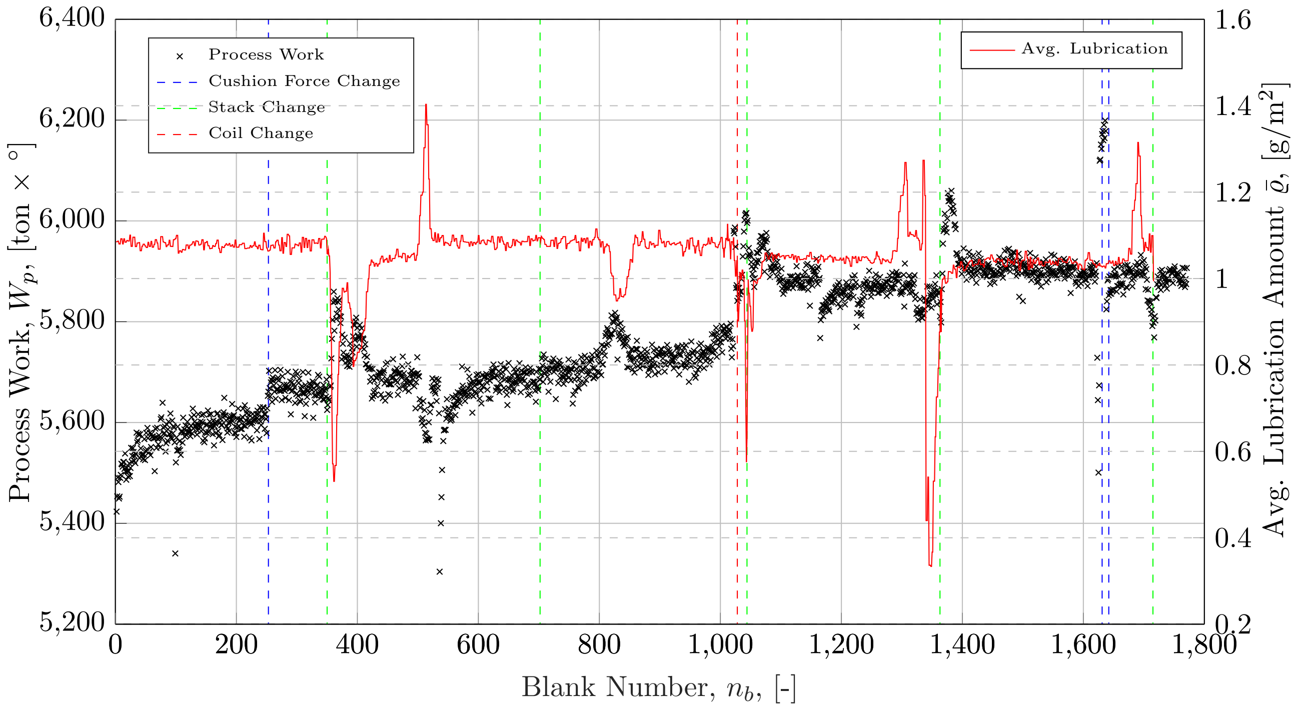


Figure 10. Average lubrication amount per blank compared to the determined process work.

concentration generally present at the edges of the coil compared to the center. For the analysis in this paper, a simplified approach is used, where an average value of the lubrication amount is determined for the blank outline bounding box. An example of the average value within the blank bounding box is shown in Figure 9(b).

By determining the average lubrication amount for each blank and overlaying this data on the results presented in Figure 8, additional insights into the process work can be gained. This is visualized in Figure 10. Notably, the sudden peak in process work starting around blank 800 coincides with a sharp decrease in lubrication amount. This supports the previously proposed hypothesis that the spike in process work was caused by a sudden change in lubrication conditions. In general, it appears that a decrease in the average lubrication amount leads to an increase in process work. This is consistent with the understanding that reduced lubrication results in higher friction between the blank and the tools [11].

Upon examining the average lubrication amount, it becomes apparent that the changes in process work associated with stack changes are likely due to variations in lubrication conditions. This is particularly evident when observing the initial stack change around blank 350 and the coil and stack change around blank 1030. For the coil change, it is observed that a generally lower lubrication amount is present, suggesting that the increased process work, previously attributed solely to changes in material parameters, is now likely due to a combination of a stronger material and a reduced lubrication amount.

The reasons behind the remaining changes in lubrication conditions coinciding with stack changes will require further investigation in a future study.

4. Conclusion

The primary objective of calculating process work is to obtain a simple parameter capable of identifying changes in process conditions. Two numerical integration methods were investigated:

the trapezoidal rule and Simpson's 3/8 rule. Based on a sample dataset, it was found that the estimated process work did not significantly differ between the two methods; however, the Simpson 3/8 rule exhibited a considerably lower estimation error compared to the trapezoidal rule.

The study further tested the method in an industrial setting. A batch of Volvo XC90 front door inner components was monitored, and the process work for each blank was determined. Analysis of the process work revealed that the method effectively captured changes in applied cushion force and material coil. A more detailed analysis, incorporating the average lubrication amount per blank, demonstrated that the process work also accurately reflects changes in lubrication conditions.

The results presented in this study provide an initial indication that determining process work can offer a relatively low-cost and efficient approach for in-line monitoring of process health. However, further refinement of the method is necessary to establish the boundaries that define a healthy process, particularly in terms of distinguishing between acceptable and failed components.

Acknowledgments

The research leading to these results has received funding from the European Union's Horizon Europe programme under grant agreement No 101177798 – CiSMA project. Funded by the European Union. Views and opinions expressed are however those of the author(s) only and do not necessarily reflect those of the European Union or HADEA. Neither the European Union nor the granting authority can be held responsible for them.

References

[1] Powell, D., Magnanini, M. C., Colledani, M. and Myklebust, O. (2022) Advancing zero defect manufacturing: A state-of-the-art perspective and future research directions. *Comput. Ind.* **136**, pp. 103596.

[2] Vollmer, R. and Palm, C. (2019) Process Monitoring and Real Time Algorithmic for Hot Stamping Lines. *Procedia Manuf.* **29**, pp. 256-263.

[3] Kunze, I., Niemietz, P, Tirpitz, L. *et al.* (2021) Detecting Out-Of-Control Sensor Signals in Sheet Metal Forming using In-Network Computing. *2021 IEEE 30th International Symposium on Industrial Electronics (ISIE)*, Kyoto, Japan, pp. 1-6.

[4] Chezan, A. R., Atzema, E. H., Pilthammar, J. and Sigvant, M. (2023) Material variability effects on automotive part production process. *IOP Conf. Ser.: Mater. Sci. Eng.* **1284**, pp. 012037.

[5] Maier, L., Ünver, B., Volk, W. and Hartmann, C. (2024) Simulation-based data reduction and data processing for sheet metal forming in the hybrid twin framework. *Int. J. Adv. Manuf. Technol.* **134**, pp. 261-269.

[6] Barlo, A., Aeddula, O., Chezan, A. R. *et al.* (2024) Creating a Virtual Shadow of the Manufacturing of Automotive Components. *IOP Conf. Ser.: Mater. Sci. Eng. 1307*, pp. 012037.

[7] Liu, H. Dhawan, S., Yang, X. *et al.* (2025) 'Generic exploration' of metal forming processes through information absent and fragmental data processing. *J. Manuf. Systs.* **79**, pp. 286-300.

[8] Kreyszig, E., Kreyszig, H. and Norminton, E. (2011) *Advanced Engineering Mathematics.* Wiley, Hoboken, NJ, **10th Edn**.

[9] Lund, E. and Condra, T. J. (2016) Notes and Exercises for Numerical Methods. [Lecture Notes] *M-MP-B5-3 Numerical Methods.* Aalborg University.

[10] Barlo, A., Sigvant, M. and Pilthammar, J. (2024) Investigation of Temperature Impact on Friction Conditions in Running Production of Automotive Body Components. *IOP Conf. Ser.: Mater. Sci. Eng.* **1307**, pp. 012004

[11] Hol, J. (2013). Multi-scale friction modeling for sheet metal forming. [PhD Thesis - Research UT, graduation UT, University of Twente]. University of Twente.