Max Weiner
max.weiner@imf.tu-freiberg.de
Conceptualization, Methodology, Software, Formal analysis, Validation, Investigation, Writing - Original Draft
Institute of Metals Forming, TU Bergakademie Freiberg

Christoph Renzing
christoph.renzing@imf.tu-freiberg.de
Conceptualization, Methodology, Software, Formal analysis, Validation, Investigation, Project administration, Writing - Original Draft
Institute of Metals Forming, TU Bergakademie Freiberg

Matthias Schmidtchen
matthias.schmidtchen@imf.tu-freiberg.de
Conceptualization, Supervision, Resources, Project administration, Writing - Review & Editing
Institute of Metals Forming, TU Bergakademie Freiberg

Ulrich Prahl
ulrich.prahl@imf.tu-freiberg.de
Supervision, Resources, Writing - Review & Editing
Institute of Metals Forming, TU Bergakademie Freiberg

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Data Availability
Data openly available in a public repository that does not issue DOIs. Source code and data are available on GitHub at the following URLs:

Project Home `https://github.com/pyroll-project`

Core Package `https://github.com/pyroll-project/pyroll-core`

Benchmark Input and Data `https://github.com/pyroll-project/pyroll-pub1-benchmark`

Conflicts of Interest
The authors declare no conflicts of interest.

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Rolling Process Variation Estimation Using a Monte-Carlo Method

M. Weiner * C. Renzing M. Schmidtchen U. Prahl

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1 Introduction

The term Monte Carlo Method (MCM) generally refers to a class of methods, which are characterized by the use of random numbers. These methods are rather diverse and serve different purposes. Here, the term shall be used for the concept of drawing random numbers as input for a function and analysing the results of several evaluations of this function, with different random inputs, with statistical methods. A detailed overview on this type of Monte Carlo methods is given by Lemieux [1]. The nature of the function can be complex, even of a black-box type, where nothing about the internals of the function is known but the input and output interfaces. In this case, Monte Carlo methods can provide valuable information about the behavior of the function while altering inputs.

Here, the function equals the simulation procedure, so it is generally known, but complex. For example, it is generally not possible, to compute derivatives of the outputs in dependence on the inputs in an analytical way. Even numerical derivation is hard, due to the multi-dimensional nature of most natural or technical systems.

The use of Monte Carlo methods for the analysis of variations in technical processes was reported before in the field of assembly of complex structures, like in mechanical engineering and building construction (f.e. [2, 3, 4, 5, 6, 7]). However, in the field of rolling processes, there was no such attempt yet to the knowledge of the authors. The authors have previously used a similar approach to model powder morphology influences in sintering processes [8, 9]. The current work shall show the possibility of the application of Monte Carlo methods for the analysis of process variations in rolling processes. The focus lies hereby on the estimation of the workpiece temperature evolution. The temperature evolution is crucial for the microstructure development of the workpiece, which shall be investigated in a following work. The influence of variations in the initial workpiece and within the regarded process route is analysed and evaluated. Due to the need of a large number of function evaluations (simulation runs), the evaluation speed of the process model is crucial to the applicability of this approach.

Rolling simulation is currently dominated by the use of finite element (FE) based models. These are offering high accuracy and high resolution results at the expense of high computational resource usage. So these methods are inconvenient for the current need. Therefore, one-

*Corresponding author

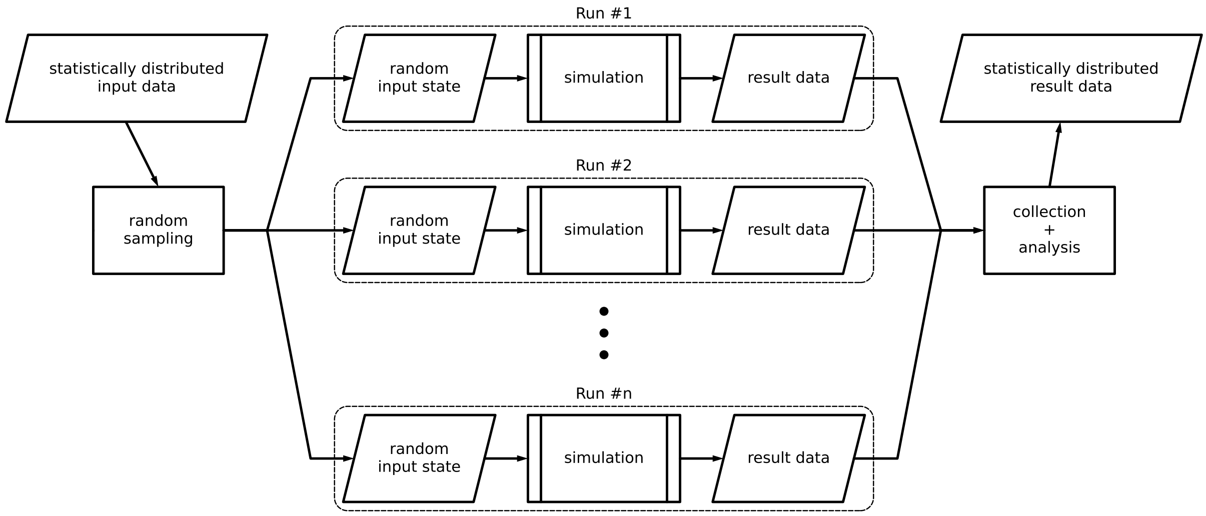

Figure 1: Chart of the Concept of Variation Estimation Using Monte Carlo Techniques

dimensional approaches shall be used here. These offer less accuracy and limited resolution, but are computable within fractions of seconds on typical personal computer systems. The current work is based on the open-source rolling simulation framework PyRolL [10], developed by the authors, which is a fast, open and flexible software package mainly aimed at groove rolling in reduction passes. The models used for the different parts of the problem can be exchanged and extended with low effort to the users needs.

2 Methods

2.1 Experimental Procedure

The Institute of Metal Forming operates a semi-continuous experimental rolling plant, which is the object of the current investigation. It consists of a two-high reversing roughing stand and four continuous finishing stands. The pass schedule of the current work consists of 10 oval-round reversing passes followed by 4 oval-round continuous finishing passes. A 50 mm round workpiece made of a mild structural steel is rolled down to 8 mm diameter. Details of the schedule are provided in the supplemental material [**esaform2023_weiner_supp**], as the exact properties of the pass schedule are of minor importance for the statements of this work.

2.2 Monte-Carlo Approach

The basic idea of the approach shown here is to simulate the rolling process several times with different input values, which are drawn by a random number generator according to predefined statistical distributions. Afterwards, the distribution of the results can be analysed by classic methods of descriptive statistics to obtain information about the process' variational behavior. The principle is shown in Figure 1.

This approach provides information about the overall variational behavior of the process. If a single source of variation is introduced in the input, the reaction of the process on this variable can be analysed. The count of variation sources introduced is generally unbounded. The tracing back of result variations to the input can be done using classic correlation methods of descriptive statistics, however, with the same typical caveats. The main benefit of the approach is, that no information about the internals of the simulation procedure is needed for variational analysis, especially there is no need for derivatives of result values in dependence on the input. The simulation procedure can generally be treated as black box with defined input and output interfaces.

The key problem is to obtain data describing the variations of the input variables. In this work two showcases shall be regarded: first the variation of the initial workpiece in diameter and temperature, second the variation of the inter-pass durations between the reversing passes. This choice was taken, since two fundamentally different types of variation sources were suspected. First, sources in the initial workpiece, which are applied only once, but traverse the whole process line. Second, variations in the process itself, which affect the workpiece state in each process step anew.

The question of varying inter-pass durations is crucial for scientific experiments on microstructure evolution, but currently often neglected. Mostly, only flat durations between the reversing passes are included in the design calculations. Due to manual transport and feed of the workpiece to the following roll pass, the scheduled inter-pass durations are never realized in practice. Although, these deviations from the schedule influence the microstructure evolution of the sample, as well as the actual conditions in the roll passes. The current approach is aimed to help quantifying these deviations.

2.3 Statistical Data Acquisition

The pilot plant at IMF is equipped with several measurement and data collection systems. Data from a number of rolling trials have been collected and analysed to obtain the interpass durations t_P between the reversing passes. The complete dataset and analysis routines are available in the supplemental material [**esaform2023_weiner_supp**].

For the approximative description of the durations' distribution, a gamma distribution was used, which is a generalized exponential distribution. The probability density function (PDF) of the gamma distribution is defined as in Equation 1, where Γ is the gamma function and $\alpha > 0$ and $\beta > 0$ are parameters.

$$f(x) = \frac{\beta^\alpha}{\Gamma(\alpha)} x^{\alpha-1} \exp(-\beta x) \tag{1}$$

Since the gamma distribution is only defined for $x > 0$, but no interpass durations below a certain value occur due to technical restrictions, the distribution was modified by introducing a minimal interpass duration $t_{\mathrm{P}0}$ with $x = t_\mathrm{P} - t_{\mathrm{P}0}$. So there are three free parameters α, β and $t_{\mathrm{P}0}$ for fitting of the distribution function. The fitting is done using least squares optimization of the resulting PDF function on the density histogram of the data.

2.4 Core Simulation Procedure

In the current work, the open-source rolling simulation framework PyRolL [11] was used to simulate the rolling process. Generally, the shown approach can be used with every rolling simulation software available, since the procedure does not depend on any internals of the simulation. A fast simulation approach, however, is favourable, since the simulation has to be done several, up to hundreds of, times. The models used here are of one-dimensional type, thus, they lack of resolution in other directions as the rolling direction and provide only limited accuracy, but at the benefit of high solution speed. They typically combine empirical approaches with simplified analytical solutions. The simulation was done with the basic configuration of PyRolL, which includes the empirical roll force and torque model of **Hensel1978**, an integral thermal model approach according to **Hensel1990**, contact area estimation according to **Zouhar1960** and roll flattening according to **Hitchcock1935**. Spreading was simulated using the equivalent flat pass according to **Lendl1948** [**Lendl1948**, **Lendl1948a**, **Lendl1949**] in conjunction with the spreading equation of **Wusatowski1969**. Details of software construction and model equations are provided in the documentation of PyRolL [10].

3 Results

4 Summary and Outlook

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