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Global sensitivity analysis of a feedback-controlled stochastic process model

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ABSTRACT

The purpose of the study was to investigate whether global sensitivity analysis can be utilised in concurrent process and control design to gain insight into the process and its control. This paper addresses the issue of sensitivity of a control law performance to its parameters in a dynamic, hybrid deterministic–stochastic process model. The control law under investigation is a collection of single-input, single-output type tower level controllers in a papermaking process. Global sensitivity analysis is shown to attribute higher importance to certain key parameters, thus providing valuable insight for the designer.

1. Introduction

This paper examines global sensitivity analysis (GSA) of a mill-wide control system. The purpose of this work was to investigate the potential of GSA in guiding design work in concurrent process and automation design. The current work relates to a simulation and optimisation based design framework under development, see [10,18,8,14]. Although concurrent design has been widely studied (see, e.g., [2,11] and the literature therein), in practice process design typically begins with flowsheet and equipment design, with the control of the process left as a later consideration. In contrast, the framework under development strives to start the control design as early as possible. This means that dynamic simulation models are needed early on in the design, even though not all relevant information is yet available. Consequently, the models contain a significant amount of uncertainty, especially with regard to their control system parts. This also means, therefore, that any further understanding of the model's behaviour is useful in the later phases of design, such as in process and control optimisation. The purpose of this paper is thus to investigate what insight can be gained by applying global sensitivity analysis during the early phases of process and automation design.

In this study we restrict the analysis to the control system of the model. This restriction is made since, as mentioned above, this part of the model is likely to contain the largest uncertainty. The aim of this paper is not to analyse one control loop at a time, as many methods and tools are available for that purpose (see, e.g., [15]). Rather, we take a systemic view, analysing several control loops and the process simultaneously. The studied case originates from the papermaking industry. The case control system provides system-wide control of several large storage towers. As such a control structure has an effect on several areas of the system, it follows that it should be designed together with the process structure as early on as possible.

The work presented here relies heavily on simulation models, some of which are stochastic, arising from parts of the studied process for which first principles models are nearly impossible to construct. These models are presented in Section 2. The

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decision to use partly stochastic models is also justified by the fact that early on in the design of processes and controls, the amount of available information is limited. Thus, the secondary research interest of this paper was to investigate how well global sensitivity could be applied to such models. In addition to simulation models, the present work utilises global sensitivity analysis (GSA), which is outlined in Section 3. Section 4 presents the results of the study, and the final chapter discusses the results.

2. Modelling

The modelled process is a paper mill. A schematic of such a mill is presented in Fig. 1.

The process uses two raw material streams, thermomechanical pulp (TMP) and chemical pulp (CP), which enter the mill from separate production systems. In the process leading up to the paper machine (PM), the raw materials are diluted, stored and mixed in large towers (3000 m^3) and smaller tanks or chests (400 m^3). At the PM water is removed from the pulp stock and solids are retained, raising the dry solids content from <1% to approximately 92%. The process contains recycle loops for water, recovered raw material from the disc filter (DF) and broke (discarded paper). Broke is produced when a break occurs in the paper web, upon which the entire production of the PM is passed via a dilution stage to a broke tower. When the PM runs normally it produces large reels of paper (gross production), which are inspected at a quality control (QC) block for quality and either accepted or rejected. If a reel is accepted it exits the system. If it is rejected, it enters dry broke storage for subsequent recycling via the broke tower.

The streams and volumes in the studied system contained five substances: water, TMP fibre, CP fibre, filler and ‘bad TMP fibre’. The ‘bad TMP’ component was used to model an unspecified raw material quality disturbance entering from the TMP mill or the broke system and having detrimental effects at the paper machine. Inclusion of the ‘bad TMP’ component was based on observations of the negative effect of the broke system on fibre qualities and composition which, in turn, has a negative effect on variables such as strength at the paper machine [9].

The towers containing significant amounts of solid material (i.e. TMP, CP, broke and dry broke towers) were modelled as plug-flow towers, while the rest were modelled as ideal mixers. The paper machine was modelled as a splitter module that splits the entering component mass flows with predefined coefficients called retention coefficients. A similar model was used for the disc filter. The quality control module was modelled with a stochastic model based on a long-term average with 10% of the entering reels turned into dry broke. The breaks were also modelled stochastically. This approach was adopted as breaks are notoriously difficult to predict from first principles, although several methods relying on measurement data have been reported (see [1] for a good review). In this paper, the probability of a break is nonlinearly related to a variable named ‘strength’. This does not directly refer to any real-life paper strength variables, such as tensile or tear strengths, but rather it refers to the overall tendency of the paper web to break or to refrain from breaking. More precisely, the strength, s, was calculated as:

$$s = \frac{s_{TMP} m_{TMP} + s_{CP} m_{CP} + s_{TMP\_b} m_{TMP\_b}}{s_{TMP} m_{TMP\_ref} + s_{CP} m_{CP\_ref}} \tag{1}$$

where s_i is the effect of component i on the strength, m_i is the mass flow of component i at the paper machine, and m_{i_ref} is the mass flow of component i in a reference situation. The reference situation in Eq. (1) includes no strength-degrading inputs, i.e. no bad TMP from broke or from elsewhere. Furthermore, in the reference situation the paper production was at its setpoint 36 t/h and the final paper filler content was at 22%. Also, in the reference situation the ratio $m_{TMP\_ref}/m_{CP\_ref} = 4$ and

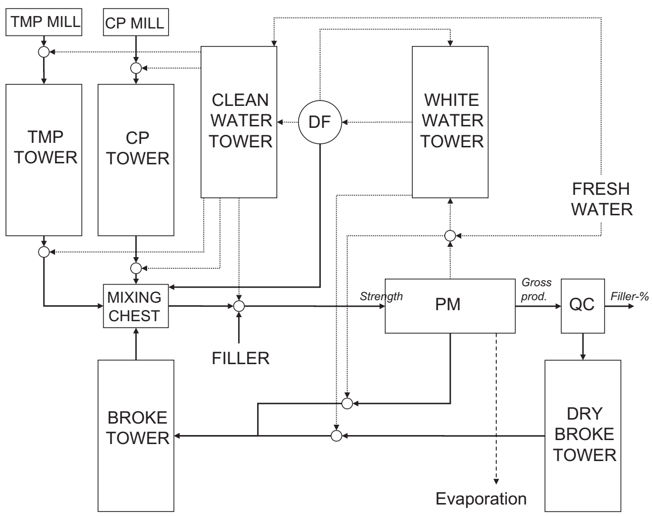

Fig. 1. Schematic flowsheet of a paper mill. The largest volumes and most critical unit operations are depicted and modelled.