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Direct product quality control for energy efficient climate controlled transport of agro-material

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Abstract

A (model-based) Product Quality Controller is presented for climate controlled operations involving agro-material, such as storage and transport. This controller belongs to the class of Model Predictive Controllers and fits in a previously developed hierarchical control structure. The new Product Quality Controller rejects disturbances and tracks the product quality by means of the product responses respiration and fermentation. To achieve an energy efficient operation the presented controller is closely linked with the (existing) local controllers. Local optimisation on the level of these local controllers allows (controlled) high-frequent climate fluctuations. This results in significant energy savings. The Product Quality Controller and the energy efficient local controllers are implemented in small-scale and full-scale industrial case studies on controlled atmosphere-container transport of apples. This yields direct control of product quality and a significant reduction in energy consumption.

Keywords: Product quality; MPC; Transport; Agro-material; Energy savings

1. Introduction

Process operations involving agro-material are confronted with tighter demands on energy efficiency and environmental pressure as well as quality requirements. These demands cannot be met by the current (local) controllers. The setpoints are determined off-line in advance and are usually constant, or, at best, manually adjusted as conditions change out of the normal. In contrast, quality variables, which are the key indicators for the performance of the overall process, are measured off-line, if measured at all, but are usually rather slow. Thus their use in control applications introduces time delays that may result in periods where the process is not operating on specifications. This paper focuses on the class of climate controlled operations like storage, transport and drying. These operations have in common the presence of different time-scales and the property of controlling the slowly reacting product with a fast-reacting environment.

To illustrate the importance of improving control in these climate controlled operations, transport of agro-material is considered in more detail. Transport of agro-material, and in particular fresh agro-food products, constitutes a significant part of the world-trade. In 1998 total value of export of these products in sea containers alone was 58.5 billion Euro for 27.7 million ton of product [11]. These transport operations operate at a relatively high level of energy use, which significantly contributes to the environmental pressure. [11] estimated that in 2010 the transport of 41 million ton of bananas, hard fruit, citrus, milk products and tropical fruits would require 3542 million kW h. Following [3] to calculate the contribution of this specific transport to the global warming problem (in total equivalent warming impact (TEWI) in kg CO_2) and using a transformation factor of 0.77 from kW h to kg CO_2 results in a conversion of 2728 million kg CO_2 each year.

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Nomenclature

C	control configuration
C_p	specific heat ($\text{J kg}^{-1}\text{ K}^{-1}$)
E	energy (J kg^{-1})
F	oxygen consumption ($\text{nmol kg}^{-1}\text{ s}^{-1}$)
H	time horizon (s)
J	objective function (Euro)
K	matrix with yield coefficients
L	costs of operation (Euro)
M	total product mass (kg)
M_a	total air mass (kg)
P	product price (Euro kg^{-1})
Q	quality attribute
R	resistance (J K^{-1})
T	temperature (K)
W	weighing factor
d	disturbance
flow	incoming air flow (kg hr^{-1})
n	mass concentration (%)
r	reaction components
t	time (s)
u	input
x	process state
y	measurable outputs
z	reconstructed state variables

Superscripts

k	iteration co-efficient
ref	reference value

Subscripts

a	air
d	direct environment state variable
dist	disturbance
evap	evaporation
ferm	fermentation
flow	incoming air flow
i	indirect environment state variable
max	maximum value
min	minimum value
n	non-reactive components
out	outside
p	primary state variable
r	reactive components
resp	respiration
u	input
y	output

The tighter demands both on energy efficiency and reduction of environmental pressure, and on the quality requirements ask for an integrated control approach, which directly aims at low-cost and low energy consumption while still full-filling the product quality demands. This requires the on-line assessment of the product's quality and a model for its prediction to provide information on a completely different level about the process.

In petro-chemical industry [2] propose a multivariate statistical controller for on-line quality improvement. Product quality is modelled performing a principal component analysis to calculate optimal setpoints for the climate variables. To overcome the problems with measuring product quality a lot of research has been done on inferential control in petro-chemical industry. An overview on this topic can be found in [5,9].

In climate controlled operations monitoring product quality by means of the product responses respiration and fermentation is discussed in e.g. [1,4,21], but these responses were not used for control purposes. [13] used a fuzzy rule-based model for the prediction of the quality degradation in drying of rice and maize as a crude measure for product quality. This measure was, however, not used for direct control of product quality. [17] use a kinetic product quality model as a constraint in a constrained model predictive controller, but no direct control of product quality was achieved. Examples of off-line optimisation of the process operation considering product quality can be found in [10] for quality of carrots and [6] for vitamin C content and non-enzymatic browning of a model food. Both are applied to drying operations. Although these developments could improve operations in food industry two problems remain. Firstly, the quality measurement is not used for feedback control, and secondly energy usage and environmental effects of the process are not considered at all.

In this paper a novel (model-based) Product Quality Controller is presented that directly controls product quality by means of the product responses respiration and fermentation. This controller defines the setpoints for the local, underlying controllers in the scheme. The local controllers are optimised for energy efficiency without harming the product.

This controller is part of a control methodology for model-based product quality control applied to climate controlled processing of agro-material. In Section 2 a brief overview of this methodology will be presented and it will be shown how the subject of this paper (direct product quality control) fits in this methodology.

The design of the controllers utilises a system model that will be discussed in Section 3. In Section 4 the control problem is stated and different types of nonlinearities are considered. In Section 5 the controllers are discussed in more detail. The applicability of the presented controller is shown using container transport of