

Model-centric technologies for support of manufacturing operations

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Abstract

In this work we discuss the impact of a series of technologies for analysis and improvement of industrial manufacturing operations. These technologies are fused in a model-centric framework for integrated simulation, estimation/reconciliation and optimization of large-scale/plant-wide industrial process systems. A continuing industrial case-study is used to illustrate the viability of these technologies and their impact on the industrial workplace.

1. Introduction

Throughout the 1990s, the computer-aided process engineering (CAPE) community made considerable progress in two strategic areas: the technical development and commercialisation of general-purpose modelling, simulation and optimisation environments; and the standardisation of open interface specifications for component-based process simulation. Contemporary commercial modelling technologies and academic research have largely engaged in the developing frameworks and methodologies for tackling the model development process; however, rigorous mechanistic process models are just one of the many components of any sophisticated software tool targeting industrial applications.

In order to succeed in their insertion in the industrial environment, model-based software tools must overcome a series of challenges limiting their ability to meet the needs of the Process Industries. First, a series of novel mechanisms and advanced software tools must be devised so that the definition of complex model-based problems is simplified. Concurrently, complementary model-based technologies must be integrated seamlessly into a single framework so that points of synergy between model-based activities for process analysis and improvements are explored systematically. In light of these facts, and considering the increasing need for comprehensive process modeling and growing scope for model-based applications (Braunschweig et al., 2000), it is clear that further research in methodologies and technologies enabling a greater sophistication of manufacturing operations would certainly be welcomed by governments, the academy and industry.

In this work we discuss the impact of a series of technologies for analysis and improvement of industrial manufacturing operations. These technologies are fused in a model-centric framework for integrated simulation, estimation/reconciliation and optimisation of large-scale/plant-wide industrial process systems. A continuing industrial case-study focussing on the pulping section of a pulp and paper plant is used

to illustrate the relevance of these technologies and their impact on the industrial workplace.

2. Evolution of general-purpose modelling languages

By the late 1990s, high-level equation-oriented declarative modelling languages abandoned their conventional scope as modelling and simulation software and embraced a more powerful and promising paradigm as unified modelling, simulation and optimisation environments (MSOEs). gPROMS is early and prominent example of such evolution. Ever since, these MSOEs have gained an increased acceptance as the most appropriate tools to tackle the modelling process when full control over the scope and detail of the process model is required (Foss et al., 1998). State-of-the-art MSOEs provide the modeller with a series of sophisticated mechanisms that contribute enormously to increase the efficiency of the modelling process. Moreover, high-level equation-oriented modelling languages benefit from the intrinsic independence between mathematical models and solution methods; thus, by segregating the mathematical definition of any given model from structural, symbolic or numerical solution algorithms, a single model description can be used to accommodate for a large number of complementary activities. As the CAPE community continues developing and validating process models, the incentive behind developing and implementing model-based applications grows. Today, the widespread adoption of these powerful multi-purpose process-engineering software tools has both motivated a genuine interest in the novel area of model-centric technologies (MCTs) and created novel and opportunities (and challenges) for advanced support of manufacturing operations.

By the mid 1990s, developers and end-users of CAPE software were confronted with the reality that commercial and proprietary process-engineering tools severely restricted the accessibility and usability of model descriptions embedded within these general-purpose modelling software. To address this problem, the CAPE-OPEN (CO) and Global CAPE-OPEN (GCO) projects were initiated. CO focussed on providing standard mechanisms to support a long-term vision according to which: process modelling components (PMCs) built or wrapped upon the standard could be incorporated into process modelling environments (PMEs) straightforwardly; and model descriptions declared within PMEs supporting the standard would be accessible to external modelling tools. This way, developers would be able to assemble software components from heterogeneous sources to solve complex model-based problems. Today, this emerging paradigm for open system architectures facilitates the development of complex mathematical process models needed to deliver even more complex model-based applications solving real-life process-engineering problems.

3. A model-centric framework as a layer for support of process operations

3.1. Characteristics

Figure 1 provides a schematic representation on how the different components of the model-centric framework described in this work are expected to support the operation of an industrial process system.

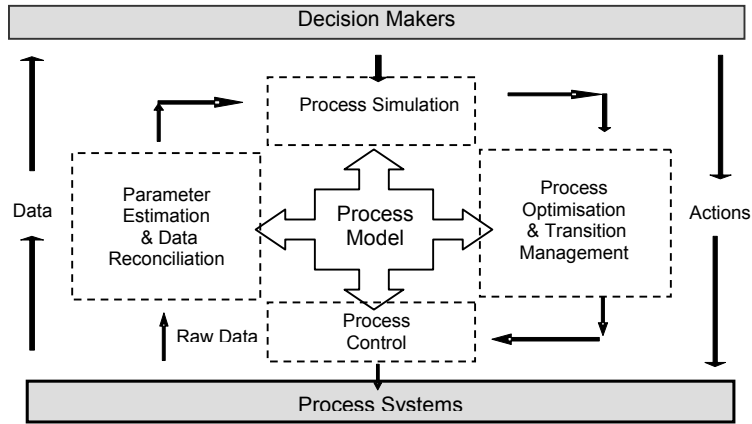


Figure 1: Schematic representation of the framework for model-centric support of process operations.

The environment for *reconstruction of process trajectories* precedes all modules that make use of raw plant data since it is imperative to obtain a consistent set of data for the robust execution of any subsequent tasks. The *estimation/reconciliation environment* incorporates dynamic parameter estimation and dynamic data reconciliation activities, which make use of consistent data sets for the estimation of process operating parameters and evaluation of process measurement biases. The information gained from these activities is presented to the decision-makers, who then have a chance to make informed decisions on issues such as process instrumentation and equipment maintenance and inventory analysis. Consistent data sets are also provided to the *simulation environment*, which extracts meaningful information from past operating conditions. An increased mechanistic understanding of fundamental transformations within the process is used for assessment of existing operative practices and training of plant personnel. The insight gained at this stage triggers the exploration of future operating conditions, which are materialised through extensive parametric sensitivity studies and assessment of novel operating policies via the customised graphical user interface of the simulation environment. The *optimisation environment* incorporates nominal process optimisation and dynamic transition planning activities. The former facilitates the investigation of operating conditions for process improvement at nominal production levels by simultaneously considering realistic operative constraints and allowing for diverse conflicting performance objectives. The latter provides a means to find operating conditions/policies to ensure the optimal transition between nominal operating levels. The knowledge gained from these activities is used by the decision-makers to update operating guidelines and manuals. Finally, the *advanced process control environment* incorporates the fundamental process model into a model-based control algorithm for on-line real-time assurance of optimal process performance under scheduled production rate changes and unexpected process disturbances and constraints.

3.2. Architecture

In order to meet the expectations of the manufacturing industries, MCTs are required to deliver high-performance model-based solutions while hindering unnecessary complexities and providing additional support to the end-users. Although MSOEs have gained increased acceptance in the academy and industry as multi-purpose modelling and solution engines (MSE), they have not been designed to facilitate the definition of realistic industrial model-based problems on-site. Therefore, MCTs targeting industrial applications should incorporate mechanisms to ease the conceptualisation of model-based problems and their implementation in the corresponding modelling language.

3.2.1. Problem Definition Component

In this work, we suggest materialising the *framework for model-centric support of process operations* proposed above by means of a *Problem Definition Component (PDC)*. As sketched in Figure 2, the PDC manages the definition of advanced model-based problems by interacting with both the PMEs and the user, while the PME executes the corresponding model-based activity by coordinating the calls to several PMCs. These PMCs contain the mathematical description of the process model, and they also provide other services such as physical property calculations and numerical solution algorithms (Braunschweig et al., 2000). Note that the standardisation of open interfaces for the PME and PMCs has been the focus of the CO/GCO projects. On the other hand, the communication between the PDC and other actors of the proposed architecture is regulated by a series of mechanisms discussed in this work and in Rolandi & Romagnoli (2005). These mechanisms entail the manipulation of the so-called *Data Model Templates (DMTs)* and *Data Model Definitions (DMDs)*.

3.2.2. Data Model Templates and Definitions

Rolandi & Romagnoli (2005) argue that, in order to ease the high-level definition of realistic model-based problems in the industrial workplace, it is necessary to provide additional meaning to end-users by including complementary information that transforms pure mathematical variables of process models into physical variables of process systems. DMTs are data models that contain this additional qualitative and quantitative information. DMTs have been conceived as extensible data structures which define the subset of process and model variables available for subsequent manipulation, their possible structural function, their nominal numerical values, and a series of advanced relational properties. In other words, DMTs determine how the process model and process-instrumentation data information can be used at higher levels of the hierarchy to define complex and realistic model-based problems driven by genuine process data. According to the characteristics of the framework described in previous sections, DMTs corresponding to *simulation*, *optimisation* and *estimation/reconciliation* activities as well as *plant data* were derived. At this point we should stress that DMTs do not necessarily represent valid model-based activities; instead, they are conceived as a kind of macro-structures from which valid simulation, optimisation, reconciliation/estimation problems can be defined.

DMDs are also data models representing *entities* of interest to process-engineers (i.e. plant data sets and simulation, optimisation and estimation activities); however, on the contrary to DMTs, these data structures correspond to valid (although not necessarily feasible) model-based activities. In brief, DMDs are a consistent mapping of the

problem definition which is derived by refining and overriding the original macro-mapping obtained from the corresponding DMT.

Overall, the DMT/DMD mechanism creates an innovative means to embed process knowledge and expertise on the definition of model-based problems, as well as increased opportunities for documentation and re-use of case-studies.

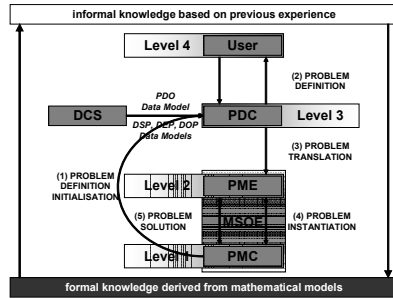


Figure 2: Architecture of the framework

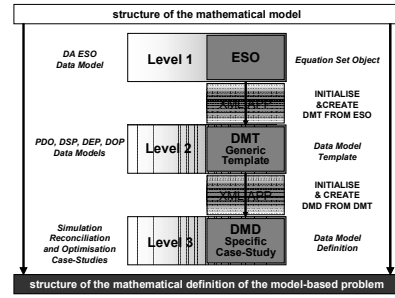


Figure 3: Sequence of definition tasks

4. An industrial case-study

We shall illustrate the benefits of the *framework for integrated model-centric support of process operations* by means of a continuing case-study; a state-of-the-art continuous pulping system of an industrial pulp and paper mill is selected for this purpose. Modern pulp and paper mills pose operability and controllability issues due to tightly coupled and closed processes. The mill used in this particular study is an excellent example of this situation, since reduced fixed capital costs were achieved at the expense of eliminating redundant (back-up) equipment and reducing inventories (hold-ups). The continuous pulping system is the heart of a pulp and paper mill; it is a network of interconnected units comprising: a feed line, a continuous cooking digester, and a heat exchange and recovery network. The daily operation of the continuous pulping process is affected by upstream and downstream disturbances that negatively influence its performance. Seasonal variations in the composition of raw materials, changes in the concentration of cooking chemicals and moisture of wood chips, and swings in the pressure of service steam are some of the conditions most often encountered, and they are likely to occur in a time scale that goes from months to hours. Concurrently, production rate changes in order to meet operational and inventory constraints and market demand fluctuations are common daily practices that negatively impact on quality indicators. The unavailability of on-line measurements of some key process variables such as selectivity and yield of the pulping reactions greatly affect the controllability of the process. Some important process disturbances such as white liquor composition and wood moisture are also unmeasured. Due to the number of units within the network of interconnected process equipment comprising the continuous pulping systems and the complexity of the physical and chemical phenomena occurring simultaneously within these units, the mechanistic process model of this industrial manufacturing system has resulted in a large-scale mathematical formulation. Using a large-scale process model to study an industrial process system under genuine

conditions of operations is a non trivial task, which has been tackled successfully with the proposed *framework for integrated model-centric support*.

5. Results

Due to space limitations only a small number of scenarios studies will be presented here.

5.1. Process simulation: performance assessment of past operating scenarios

The objective of the continuous cooking digester is to deplete lignin from the wood matrix, which is a multi-component substance that also contains cellulose and hemicelluloses. In industrial continuous cooking processes, the selectivity and yield of the pulping reactions are the key process variables indicating the *production of pulp* and *degree of delignification*, respectively. Let us examine the yield and selectivity profiles throughout the length of the continuous cooking digester as given by *historic* operating conditions. These results are shown in Figures 4 and 5. A feature that deserves our attention is the qualitative shape of these profiles during the early stages of the cooking process, at the entrance to the digester (known as the *impregnation zone*). Figure 4 shows that the wood-chip yield decreases, indicating that degradation and solubilisation of wood components is taking place. Figure 5 shows that kappa number increases in the impregnation zone, a phenomenon that has also been reported by Wisniewski et al. (1997). A simultaneous decrease of pulp yield and increase of the kappa number (a measure of selectivity) in the impregnation zone indicates that undesired solubilisation of cellulose is taking place. This is usually associated to high impregnation temperatures and high alkali concentrations. Since chemical pulping target degradation of lignin-like components but not the solubilisation of cellulose and hemicelluloses, this snapshot of the operational status of the continuous pulping system leads us to the conclusion that the performance of this industrial system could possibly be improved. This important result leads us to continuing with the following case-studies.

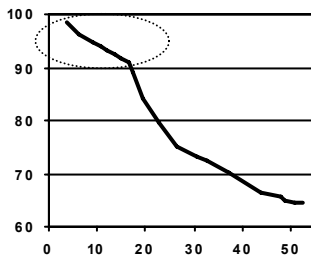


Figure 4: yield vs height

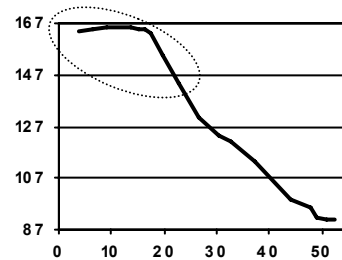


Figure 5: kappa number vs height

5.2. Process optimization: improvement of nominal operating performance

Here, two alternative scenarios are investigated aiming at improving the nominal operating conditions of the continuous pulping system: (CS1) maximum production and (CS2) maximum overall net profit.

The operating conditions suggested by CS1 increase production by 1.2% (an improvement of the pulp yield at constant selectivity) which, in turn, boosts the overall

profit of the continuous pulping system by approximately 1.04US\$/min. An analysis of the economic performance shows that the 1.68US\$/min revenue increase from a higher pulp throughput is counterbalanced by a higher flow of black liquor for evaporation (0.64US\$/min) while other sources of revenue and costs are less relevant to this study. Surprisingly, the operating conditions found in **CS2** also boost the economic performance of the continuous pulping system, although this time the overall profit increases by approximately 3.00US\$/min. Interestingly, these conditions lead to a reduction in the pulp yield of approximately 0.15% with respect to **CS1**; however, the lower pulp throughput (0.17US\$/min) also results in a considerably lower flow of black liquor for evaporation, which translates into a 3.18US\$/min expense decrease. *Compared with the original operating policy of the mill, CS2 may potentially result in 2.0 million US\$/yr additional revenue.*

5.3. Transition management: assessment of the control structure and procedure

Again, two possible scenarios are presented investigating the effect of different transition policies during production rate changes: (**CS1**) manipulation of both the lower circulation heater and the wash circulation heater controllers and (**CS2**) manipulation of the circulation heater controller solely. Figures 6 to 8 illustrate the trajectories of some key process variables under these two possible transition management scenarios.

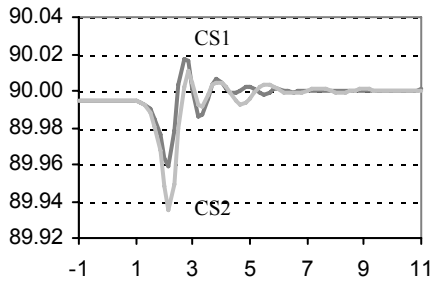


Figure 6: kappa number vs time

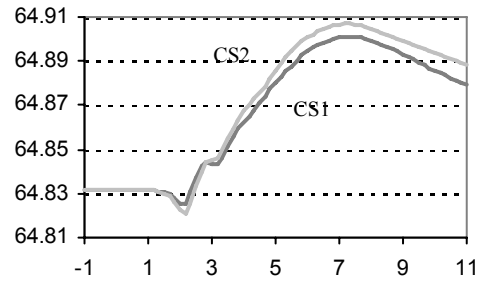


Figure 7: yield vs time

From Figure 6 we can appreciate that there are no sensible differences in the trajectory of the blow-line kappa number for **CS1** and **CS2**. Hence, the sole manipulation of the temperature set-point of the lower circulation heater during a production rate change is sufficient to reduce the variability of this key process variable significantly (i.e. **CS2**). In spite of this, Figure 7 shows that these transition management procedures are not equivalent, since **CS2** gives rise to a more efficient use of the raw materials (note the pulp yield increase). Figure 8 demonstrates that the temperature profiles along the continuous cooking digester are not the same during the transition. In **CS1**, part of the increased cooking load has been shifted to the lower cooking zone and upper section of the wash zone (the bottom of the vessel, where temperature differences of more than 0.5°C are observed). On the contrary, in **CS2** the lower cooking zone (towards the center of the vessel) has accommodated the increase in temperature counteracting the

reduction in residence time, which is known to have a positive effect on the selectivity and yield of the pulping reactions as confirmed in Figure 7. *In summary, not only have we achieved similar quality control performance, but we have also found an alternative transition management procedure which uses the raw materials (both cooking liquor and wood chips) more efficiently.*

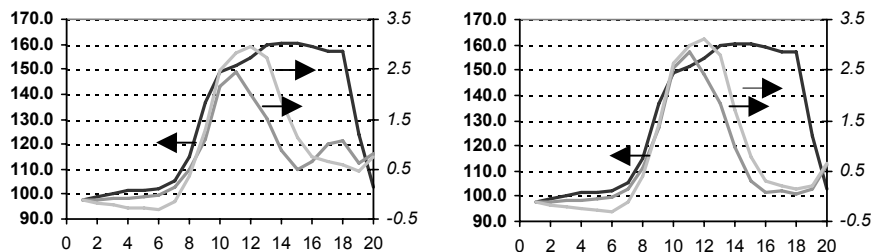


Figure 8: Reaction temperature profiles: (a) CS1 and (b) CS2; Primary y axis (lhs): absolute temperature [°C] (0hr); secondary y axis (rhs): relative temperature (difference) [°C] (4hr, 12hr);

6. Conclusions

Supporting the manufacturing operations of industrial process systems requires the consistent and integrated solution of a series of process-engineering problems. Conventionally, these problems would comprise the use of a model of the process system to solve model-based activities such as process simulation and optimization, estimation/reconciliation and advanced process control. The execution of these activities requires the definition of the corresponding model-based problem. The framework discussed in this work proposes a software architecture and methodology that eases the definition of advanced model-based process-engineering problems for support of process operations and promotes the transfer of knowledge between complementary model-based applications, especially in the context of large-scale/plant-wide industrial process systems. This research brings model-based applications for support of manufacturing operations (and model-centric technologies in general) to an unparalleled level of integration with the industrial workplace.

7. References

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