Modelling and Validating a Deoiling Hydrocylone for Fault Diagnosis using Multilevel Flow Modeling

Emil Krabbe NIELSEN[1], Mads Valentin BRAM[2], Jérôme FRUTIGER[3], Gürkan SIN[4], and Morten LIND[5]

1. Department of Electrical Engineering, Technical University of Denmark, Elektrovej 326, 2800, Denmark (ekrani@elektro.dtu.dk)
2. Department of Energy Technology, Aalborg University, Niels Bohrs Vej 8, 6700, Esbjerg (mvb@et.aau.dk)
3. Department of Chemical Engineering, Technical University of Denmark, Søltofts Plads 227, 2800, Denmark (jfru@kt.dtu.dk)
4. Department of Chemical Engineering, Technical University of Denmark, Søltofts Plads 227, 2800, Denmark (gsi@kt.dtu.dk)
5. Department of Electrical Engineering, Technical University of Denmark, Elektrovej 326, 2800, Denmark (mli@elektro.dtu.dk)

Abstract: Decision support systems are a key focus in research on developing control rooms to aid operators in making reliable decisions, and reducing incidents caused by human errors. For this purpose, models of complex systems can be developed to diagnose causes or consequences for specific alarms. Models applied in safety systems of complex and safety critical systems, require rigorous and reliable model building and testing. Multilevel Flow Modeling is a qualitative method for diagnosing faults, and has previously only been validated by subjective and qualitative means. This work aims to synthesize a procedure to measure model performance, according to diagnostic requirements, to ensure reliability during operation. A simple procedure is proposed for validating and evaluating Multilevel Flow Modeling models. For this purpose expert statements, a dynamic process simulation in K-spice, and pilot plant experiments are used for validation of two simple Multilevel Flow Modeling models of a deoiling hydrocyclone, used for water and oil separation.

Keyword: Multilevel Flow Modelling, Model Validation, Water treatment, Fault Diagnosis.

1 Introduction

Decision support systems are crucial in order to improve the efficiency and safety of control systems. With an increase in system complexity and autonomy, the tasks for operators to analyse situations, of behaviours deviating from nominal system operation, becomes increasingly complicated.

Automated fault diagnosis is a method which can potentially decrease the reaction time, and increase the probability of a correct response to faults. The focus of online fault diagnosis has primarily been on component level. Multilevel Flow Modeling (MFM), is a method for modelling the functionality of complex mass and energy flow systems. Models of nuclear power systems, electric power grids and oil production systems have been used for online fault diagnosis[1]. The method is used for modelling how low level functionality supports high level functionality, commonly referred to as means-end models.

MFM has numerous different applications of which one is online fault diagnosis. Online fault diagnosis with MFM is however limited in application[1]–[6], whereas offline root cause analysis has been applied diversely.

The purpose of this research project is to build models of an offshore water treatment system for oil production. These models will in future be used for online fault diagnosis. Initially a deoiling hydrocyclone is modelled and validated. The current methods for model validation of MFM models are limited in application, as the models primarily have been used for offline root cause analysis. For using such models for fault diagnosis in industrial decision support systems, the models must be reliable. Insufficient validation of models for improving decision reliability may prove to be counterproductive, when seeking to improve the level of safety.

No additional requirements are defined for advanced or intelligent control algorithms, and diagnostic methods in standards such as[7]. In case of false or absent alarms and diagnoses, operators may ignore such methods, and eventually solely rely on their own experience and intuition. In line with the concept of defence in depth[8], fault diagnosis is an addition to the monitoring level, at level 2, to enable either prevention or mitigation of faults.
A fault diagnostic system should thus be considered as a safety precaution to the same degree as an emergency shutdown, although it's function according to defence in depth is at a different level. Model validation is thus crucial.

This paper introduces the initial work on an approach to validating MFM models based on different types of available information. It has been applied to simple MFM models of a deoiling hydrocyclone. The aim is to provide a measure of model performance.

2 Previous validation

Multilevel Flow Modeling is a strictly qualitative method. Numerical process signal are used, but only to produce qualitative discrete states such as low or high, which are then treated by the MFM model. This simplifies the rule base and thus the reasoning process significantly, and ensures a low computational effort when dealing with plantwide fault diagnosis[1].
Systems have typically been modelled and validated by an expert in MFM and a process expert. Based on the model, functions are triggered separately, and the prognosis is compared to the causes and consequences explained by a process expert. Alternatively a MFM and/or process expert attempt to describe how the MFM prognosis, relate to the fluid mechanics of the process system. This approach is subjective and qualitative.

The majority of published research on the topic of MFM is not concerned with the validity of the models. This is very problematic, as many models are presented, with no information on how well they model the physical system. The published research addressing validation includes examples of comparison of expert opinions to cause-consequence fault trees, to counter-actions for recovery generated based on the MFM model predictions, and to fault trees published in scientific literature[9][10][11].
More recently model prongnoses have been compared to standardized operation procedures (SOP) available in published standards and numerical process simulations[12]. The SOP and MFM prognoses were presented in a table for easy comparison as a basis for a qualitative evaluation[13]. In addition different theoretical aspects of MFM model validation are discussed in[14].
The previously mentioned approaches all focus on the validity of the model based on the output produced from a specific input. The causal relations between functions have been discussed by Larsson and Berquist, and a correlation method was presented to determine the causal relationship between functions[15] [16]. The validity of the causal relationships are the only examples of validation of the structure of MFM models. Apart from this, the structure is only treated as a part of verification, according to a defined MFM syntax[14].

3 Hydrocyclone

The validation method will be used for a case on a simple model of a hydrocyclone. A hydrocyclone is a passive component used for separation of water and oil in offshore produced water treatment (PWT). It has one inlet, and two outlets. If the process conditions are optimal, the oil leaves the hydrocyclone through the overflow outlet, and the water through the underflow outlet as shown in Fig. 1.

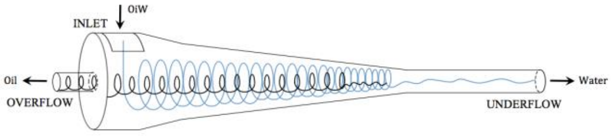

Fig. 1 Example of water and oil flow in a hydrocylone[17]

The common control strategy is based on the pressure drop ratio (PDR) defined as the ratio between the pressure difference from inlet to overflow ΔP_o and from inlet to underflow ΔP_u as shown in Equation (1)[18].

$$\boldsymbol{PDR} = \frac{\Delta \boldsymbol{P_o}}{\Delta \boldsymbol{P_u}} = \frac{\boldsymbol{P_i - P_o}}{\boldsymbol{P_i - P_o}} \quad (1)$$

As the density of water is higher than that of oil, the centrifugal force of the water exceeds the centrifugal force of the oil particles. The inlet flow enters tangentially to the conical geometry of the hydrocyclone, thus passively generating a rotating flow. This results in the water moving outwards, towards the hydrocyclone wall in a vortex, and the oil to be displaced towards the centre of the hydrocyclone, in a vortex.

The separation efficiency of the hydrocyclone, does not only depend on the PDR, but also on flow-split, inlet flow rate, oil droplet size, distribution, and geometry. The flow-split is proportional to the PDR, and it can defined as the ratio between the overflow flowrate Q_o, and the input flowrate Q_i[19]:

$$Flowsplit = \frac{Q_o}{Q_i} \quad (2)$$

The separation performance depends not only on the flow-split and PDR, but also on the oil droplet size and the oil content, two parameters which are not controlled. The PDR is controlled, by using two control valves at each outlet. The hydrocyclone used for experimental work is shown in Fig. 2. The setup has a pressure and flow sensor on all in- and outlets, and one control valve on each outlet. The input water is delivered from a water tank by a pump. Both the underflow and overflow output is transported to the same water tank.

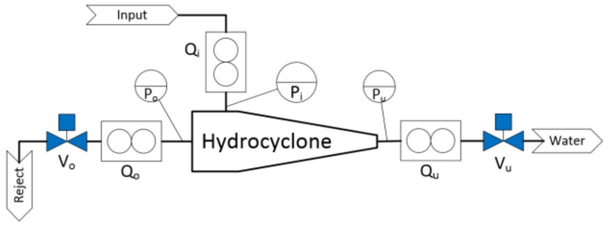

Fig. 2 P&ID of the hydrocyclone at the pilot plant.

The standard offshore application of hydrocyclones involves upstream separation, in three-phase separation tanks. The underflow valve is then used for controlling the water level in the three-phase separation tank, and the overflow valve controls the PDR.

In this application, any other processes but the hydrocyclone are bypassed, and the underflow valve has no real-time control. In a standard application, the hydrocyclone is placed in a bundle of hydrocyclones, between which the inlet water is split. This is however not the case in this particular application, where only a single hydrocyclone is used.

4 MFM Model

As a case study, only a part of the full MFM model of the hydrocyclone will be used to prove and present the principle of this validation method. This part is the mass flow, shown in Fig. 3. As can be seen from the figure, there are six transport functions, of which three represent the three flowrate sensors, and three storage functions representing the pressure sensors. A balance represents the mass balance of flow from inlet to underflow and overflow.

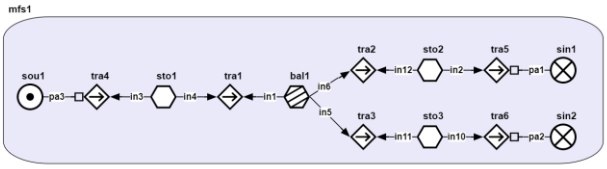

Fig. 3 MFM Model of hydrocyclone mass flow separation.

The model shown in Fig. 3, can potentially be used as two different models, by having two different representations of the sensors. The component to function mapping will thus be the only difference between the two models. The two models and their respective mappings are shown in Table 1.

Table 1 MFM Models

Model	Q_i	Q_u	Q_o	P_i	P_u	P_o
MFM v1.0	tra1	tra3	tra2	sto1	sto3	sto2
MFM v1.1	tra4	tra6	tra5	sto1	sto3	sto2

5 Validation Method

The purpose of having a structured methodology for validating MFM models for fault diagnostic applications includes:

1. Performance comparison of one model, on different sets of faults, to determine the suitability of MFM models for specific faults or systems.
2. Comparison of different models and versions on the same set of faults to track and ensure progression during model building.
3. Comparison of different versions of the MFM methodology on the same set of faults, to track and ensure improvement on development of the MFM methodology of e.g. the rule base and reasoning.
4. Performance comparison of MFM with other fault diagnostic methods on the same set of faults, to determine the suitability of MFM for specific systems or faults, compared to other methods.

A graphical illustration of these four purposes, are shown in Fig. 4. The figure depicts defined sets of faults, marked by bold circles, in comparison to diagnostic prognoses (predictions), marked by filled circles. If a model can predict all of the defined faults, the bold and filled circles align, and are equal in size.

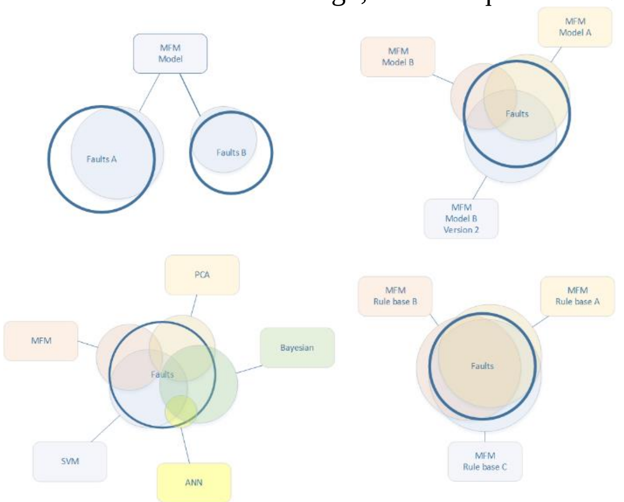

Fig. 4 Model comparison of MFM on fault sets by performance evaluation.

The model validation of MFM models can be separated into three stages, based on the available information at each stage. These stages are *System Concept*, *System Design* and *System Operation*.

In the first stage, *System Concept*, when generating the system concept, the only available information may very well be P&ID diagrams, expert opinions and preliminary Hazard and Operability Study (HAZOP) results. This information can be used to build the MFM model, and validate it. In the next stage, *System Design*, flowsheets, mass, energy and momentum balance calculations, process module specifications and Dynamic Process Simulations (DPS) may be available. *System Operation*, the final step, could very well be carried out as a part of commissioning. At this stage, the physical system is available for experimentation, and can thus include online fault diagnosis of faults emulated on the physical plant. For this work, a pilot plant (PP) of an offshore system will be used. The validation procedure for each stage is shown in Fig. 5.

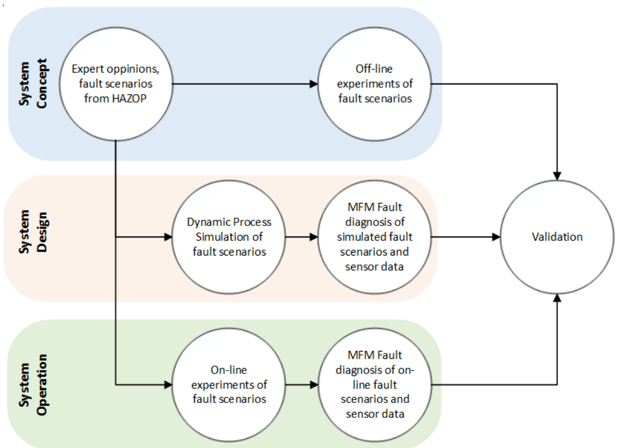

Fig. 5 Modeling and validation stages of MFM models.

The previously published validation approaches, are all related to the System Concept stage, apart from the methods introduced by Larsson and Wu. The validation of MFM models at each stage can be considered as engineering validation of the models. Future work will include a scientific validation of the three engineering validation approaches, by combining the models and information of different types, from each of the three stages, to examine the discrepancies between the models. In the case of no or only little discrepancy, it is assumed that models can be validated at each stage, by using this procedure.

6 Validation

Conventional diagnostic methods are used for modelling a specific set of faults, to distinguish between these, and any other behaviour. In theory, MFM can distinguish between faults, that have not been defined. The models describes the systems at a generic and qualitative level, capable of generating propagation paths and prognoses automatically, based on evidence.

For this reason, it is important to also validate the structure of the model and not only the prognoses. To increase the fidelity of such prognoses, it is important that the model representation of the system behaviour, functionality, and causality is correct. This paper deals with the validity of relations between functions, to determine how well they reflect the physical system.

If such relations are valid, the non-validated prognoses of the MFM model, will be assumed correct. As an example, four scenarios have been defined and tested for each of the three stages. The valve positions of V_u and V_o have been opened and closed a defined amount individually. The fault is implemented as a position control offset of the valve setpoint (SP) in both the DPS, and on the PP. An overview of how the fault has been implemented in MFM, on the PP, in the DPS, and as expert statements is shown in Table 2. The valve position range for V_u and V_o is [0 100%] where 0 is fully closed, and 100% is fully fully opened.

Table 2 MFM Models

Fault	Expert	DPS	PP	MFM
V_u ÷	V_u close	V_u SP ÷3 %	V_u SP ÷3 %	Q_u Low
V_u +	V_u open	V_u SP +3 %	V_u SP +3 %	Q_u High
V_o ÷	V_o close	V_o SP ÷20 %	V_o SP ÷20 %	Q_o Low
V_o +	V_o open	V_o SP +20 %	V_o SP +20 %	Q_o High

1.1 System Concept

At the concept level, no numerical information will be available, apart from what can be found in literature. The only other source of information at this stage, will most likely be estimations and experience-based statements of experts. When designing chemical process systems, a Hazard and Operability Study (HAZOP) will be carried out, for compliance with safety. The format of a HAZOP is as follows:

1. Which hazards can arise, given a physical property (flowrate) changes (increases) in the hydrocyclone?
2. What are the causes?
3. What are the consequences?
4. What are the safeguards?

Thus, the purpose is not to identify the system behavior but to identify safety critical operation, and the corresponding causes and consequences. In addition, safeguards must be proposed to alleviate faults. However as it is based on a physical property such as the flowrate, and an instance such as a decrease, it can be used as a basis for specifying the operational behaviour in a structured manner when identifying causes and consequences of the given properties. A HAZOP is based solely on expert statements. For this work expert statements have been acquired from operators of the pilot plant and compiled into a *Qualitative Trend Table* (QTT) in Table 3, instead of collecting them by a HAZOP. In all the QTTs the + represents an increasing qualitative trend of a property, and ÷ a decreasing qualitative trend. Each column represents a physical property, and the rows represents scenarios.

Table 3 QTT for Expert statements

	Q_i	Q_u	Q_o	P_i	P_u	P_o	PDR	F_s
V_u +	+	+	+	÷	÷	+		
V_u ÷	÷	÷	÷	+	+	÷		
V_o +	+	÷	+	÷	÷	÷		
V_o ÷	÷	+	÷	+	+	+		

6.2 System Design

The hydrocyclone of the pilot plant has been modelled in K-Spice for a dynamic process simulation. K-Spice is a software for simulating process conditions of offshore oil production plants, with the intent of plant design.

The model includes a hydrocyclone module, an overflow and an underflow control valve, and a PID controller for the overflow valve. The underflow valve has been given a specified setpoint, with no control. The model is shown in Fig. 6. This model has not been calibrated, and thus produces results different from that of the pilot plant. It is assumed that this difference is only numerical, but no differences exist at a qualitative level between the pilot plant, and the model behaviour.

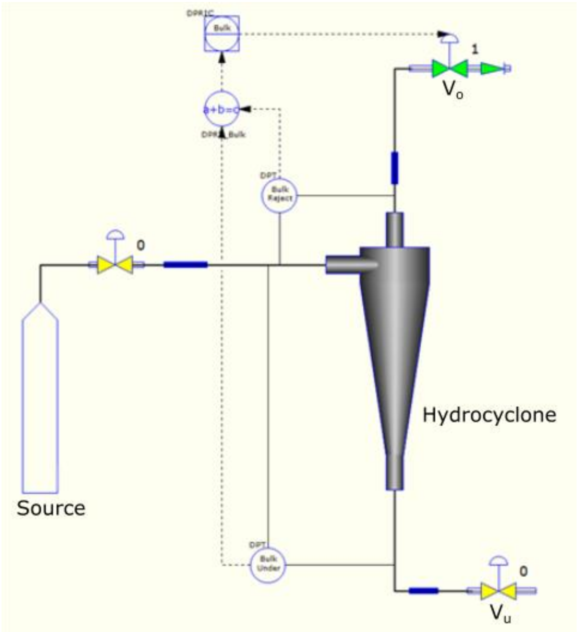

Fig. 6. Model of a hydrocyclone in K-Spice.

A table similar to Table 3, has been compiled based on the experiments for the dynamic process simulation outlined in Table 2.

The scenario of a closing overflow valve is shown in Fig. 7 for the overflow valve position, and the inlet, underflow and overflow pressure. It is assumed that the magnitude of an increase or decrease not is of importance for assessing the validity of how a high or low evidence from an alarm, is propagated through a model.

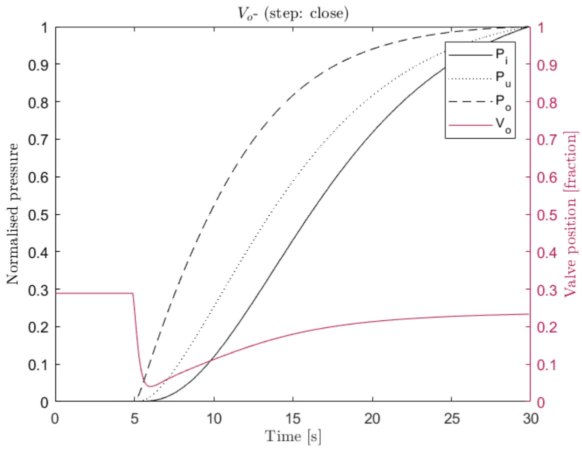

Fig. 7. Closing overflow valve V_o DPS.

The relationship between the three different pressures can be seen on Fig. 7. As the valve is closed, the pressure increases at inlet, underflow and overflow. This does however not necessarily give any indication of causality, and the increase could potentially be due to something different. Such causality could be investigated by statistical correlation methods[15].

Another model which will not be discussed here, has been included in the validation. It is a Flow Resistance based model (FR) of the hydrocyclone[17]. The V_u and V_o valves have been stepped individually in the range [0 1] to form a grid. At each valve position of V_o the physical properties have been averaged over all steps of V_u. The same is done for each valve position V_u, as an average of V_o.

The flowrate is shown as a function of V_o positions in Fig. 8. A linear curve has been fitted to the model, to determine whether the flowrate decreases or increases, when closing or opening the valve. This procedure has been carried out for all physical properties Q_i, Q_u, Q_o, P_u, and P_o by using the model, and fitting a linear curve to the model. The results have been compiled into a table similar to Table 3, for the FR model.

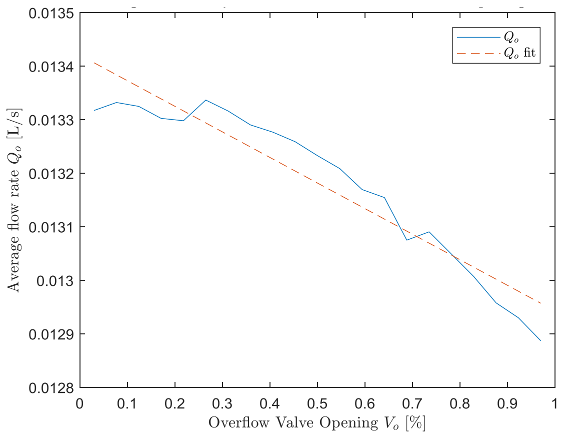

Fig. 8 Average flowrate Q_o of valve positions V_o for FR model.

Similar to the FR model, a linear curve has been fitted to the process signals shown in Fig. 7, to determine the qualitative trend of the DPS, to produce a table similar to Table 3.

6.3 System Operation

A scenario for opening the underflow valve on the pilot plant is shown in Fig. 9. The qualitative trend of all sensor signals, for each of the four scenarios have been found by fitting linear curves to the empirical data, to produce Table 4.

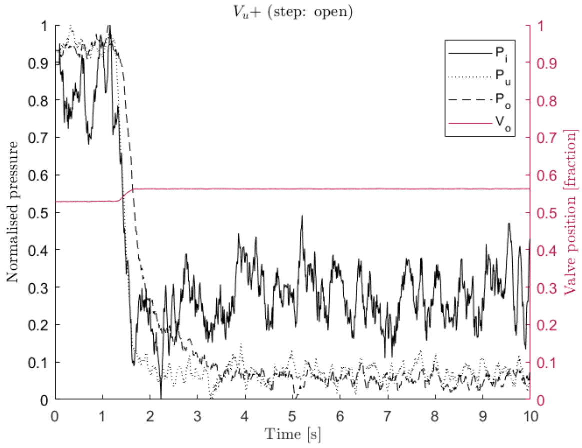

Fig. 9. Opening Vu on Pilot Plant.

Table 4 QTT for Pilot plant experiments

	Q_i	Q_u	Q_o	P_i	P_u	P_o	PDR	F_s
V_u +	+	+	÷	÷	÷	÷	÷	÷
V_u ÷	÷	÷	÷	+	+	+	÷	÷
V_o +	+	÷	+	÷	÷	÷	+	+
V_o ÷	÷	+	÷	÷	÷	+	÷	÷

6.4 Evaluation

The two MFM models have been used to produce QTTs. For each model, Q_u has been triggered in cause reasoning for the V_u case as either high or low, and Q_o in the V_o case. The resulting QTT for the v1.1 model is shown in Table 5.

Table 5 QTT for MFM Model v1.1

	Q_i	Q_u	Q_o	P_i	P_u	P_o	PDR	F_s
V_u +	+	+	÷	÷	÷	÷		
V_u ÷	÷	÷	÷	+	+	+		
V_o +	+	÷	+	÷	÷	÷		
V_o ÷	÷	+	÷	+	+	+		

All QTTs have been compared separately to the MFM models' QTTs, and a voted QTT has been constructed based on agreement of the majority of models. For each fault, the MFM model has been compared to the other models separately with confusion matrices as shown in Table 6.

Table 6 Confusion Matrix: Q_i for V_u+ with DPS

Q_i for V_u+		**Predicted MFM**	
		+	÷
Observed DPS	+	TP	FP
	÷	FN	TN

The simulated behaviour by the MFM model is considered as a prediction, and the other models as real observations. In this way the qualitative trend for all sensor values (Q_i, Q_u, etc.) of the MFM model in Table 5, has been compared to the trend of the other models' QTTs. The predictions have been grouped as true positive (TP), true negative (TN), false positive (FP), and false negative (FN). Based on this, the *Accuracy* of the MFM model has been calculated as:

$$\boldsymbol{Accuracy} = \frac{\boldsymbol{TP + TN}}{\boldsymbol{TP + TN + FP + FN}} \quad (1)$$

The accuracy of the MFM models is shown based on the real observations from each of the other models (DPS, PP, Expert, FR, Voted) in Table 7.

Table 7 Model performance

Model	PP	DPS	Expert	FR	Voted
MFM v1.0	0.71	0.75	0.8	0.8	0.83
MFM v1.1	0.86	0.92	1	1	1

It is evident from Table 7, that the MFM model v1.1 is a better representation of the sensors (components) in the MFM model, than that of v1.0.

This approach allows to measure model progression and improvement, and could potentially also be used as a quantitative approach to assess if changes to the Multilevel Flow Modeling methodology improves MFM's ability to represent process systems.
A similar approach to the work presented here, will be investigated and applied, for the purpose of validating MFM model predictions. The purpose will be to suggest an approach for model validation, by measuring how well MFM models can predict root causes or consequences in real-time on industrial systems.

8 Conclusion

An approach has been presented for validating the causal structure of MFM models, in order to measure model performance and ensure progression of model building. The approach identifies three stages at which MFM models can be validated with three different types of information: a concept, design and operation stage of process systems. The approach has been applied on two simple MFM models of a deoiling hydrocyclone for offshore PWT. Expert statements, a dynamic process simulation in K-Spice, an empirical Flow Resistance based model, empirical data from a pilot plant, and a voting based model have been used for model validation. A metric from binary classification has been used for evaluating the MFM model coherence with evidence from the other approaches. The combined voting model had the best coherence with both MFM models.

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References

[1] J. E. Larsson, "Real-Time Root Cause Analysis with Multilevel Flow Models," International Workshop on Principles of Diagnosis, pp. 3–8, 2009.
[2] J. E. Larsson, B. Öhman, and A. Calzada, "Real-Time Root Cause Analysis for Power Grids," Security and Reliability of Electric Power Systems, pp. 1–7, 2007.
[3] J. E. Larsson, "On-Line Root Cause Analysis For Nuclear Power Plant Control Rooms," Proceedings of the International Symposium on Symbiotic Nuclear Power Systems for the 21st Century, 2007.
[4] J. E. Larsson and J. DeBor, "Real-time root cause analysis for complex technical systems," IEEE 8th Hum. Factors Power Plants HPRCT 13th Annu. Meet., pp. 156–163, 2007.
[5] J. E. Larsson, "On-line Root Cause Analysis for Large Control Centers." 2005.
[6] H. P.-J. Thunem, "The development of the MFM Editor and its applicability for supervision, diagnosis and prognosis," Safety, Reliability and Risk Analysis: Beyond the Horizon, pp. 1807–1814, 2014.
[7] Norwegian Technology Centre, "NORSOK STANDARD Safety and automation system (SAS)," 2001.
[8] International Nuclear Safety Advisory Group, Defence in Depth in Nuclear Safety, 1996.
[9] A. Gofuku, S. Koide, and N. Shimada, "Fault Tree Analysis and Failure Mode Effects Analysis Based on Multi-level Flow Modeling and Causality Estimation," International Workshop on Safety and Maintenance of Engineering Systems, pp. 497–500, 2006.
[10] A. Gofuku and Y. Tanaka, "Display of diagnostic information from multiple viewpoints in anomalous situation of complex plants," IEEE International Conference on Systems, Man, and Cybernetics, Vol. 5, pp. 642–647, 1999.
[11] A. Gofuku and A. Ohara, "A Systematic Fault Tree Analysis Based on Multi-level Flow Modeling," Prog. Nucl. Saf. Symbiosis Sustain. Adv. Digit. Instrumentation, Control Inf. Syst. Nucl. Power Plants, pp. 97–103, 2014.
[12] J. Wu, L. Zhang, J. Hu, M. Lind, X. Zhang, S. B. Jørgensen, G. Sin, and N. Jensen, "An Integrated Qualitative and Quantitative Modeling Framework for Computer-Assisted HAZOP Studies," Am. Inst. Chem. Eng., Vol. 60, No. 12, pp. 4150–4173, 2014.
[13] J. Wu, M. Lind, X. Zhang, S. B. Jørgensen, and G. Sin, "Validation of a functional model for integration of safety into process system design," 12th International Symposium on Process Systems Engineering and 25th European Symposium on Computer Aided Process Engineering, pp. 293–298, 2015.
[14] J. Wu, L. Zhang, S. B. Jørgensen, N. Jensen, X. Zhang, and M. Lind, "Procedure for validation of a functional model of a central heating system," World Conference of Safety of Oil and Gas Industry, 2014.

[15] T. Bergquist, J. Ahnlund, J. E. Larsson, and L. Spaanenburg, "Using Correlation in MFM Model Design and Validation," Proceedings AILS-04 Workshop, 2004.
[16] J. E. Larsson, J. Ahnlund, T. Bergquist, F. Dahlstrand, B. Öhman, and L. Spaanenburg, "Improving Expressional Power and Validation for Multilevel Flow Models," J. Intell. Fuzzy Syst. Appl. Eng. Technol., Vol. 15, No. 1, pp. 61–73, 2004.
[17] M. V Bram, L. Hansen, D. S. Hansen, and Z. Yang, "Grey-Box Modeling of an Offshore Deoiling Hydrocyclone System," Conference on Control Technology Applications, 2017.
[18] P. Durdevic, S. Pedersen, M. Bram, D. Hansen, A. Hassan, and Z. Yang, "Control Oriented Modeling of a De-oiling Hydrocyclone," IFAC-PapersOnLine, Vol. 48, No. 28, pp. 291–296, 2015.
[19] Z. Yang, S. Pedersen, and P. Durdevic, "Cleaning the Produced Water in Offshore Oil Production by Using Plant-wide Optimal Control Strategy," Oceans - St. John's, pp. 1-10, 2014.