

Financial Services Industry: Continuous Model Monitoring

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Abstract

In this paper we articulate our view of the next step in the evolution of Model Risk Management – Continuous Model Monitoring (CMM). Our contention is that existing model governance processes are in general fairly robust except in one important respect; the ongoing model performance monitoring that occurs after a model is initially approved for use. While most banks have some form of model monitoring process in place and some go even further in terms of dedicated functions for this purpose for some categories of model, the frequency, scope and breadth of testing is in most cases insufficient to identify many potential model issues before a problem materialises.

To address this shortcoming we propose that existing model governance processes are enhanced to incorporate a formalised CMM activity, owned by a dedicated function. This would be an independent component of the overall governance process. The remit of the CMM function is to implement, execute and analyse model performance tests on a systematic, consolidated and ongoing high-frequency basis. Our hypothesis is that by constantly tracking a model's performance against specified metrics, we can identify emerging trends in a model's performance proactively, rather than reacting to issues that have already arisen and may be costly to remediate. Such an early warning system can assist with the ongoing, controlled, evolution of a model as market conditions change, potentially avoiding the need for costly, discontinuous model changes.

CMM, in the form that we are proposing, represents a step-change in the model performance monitoring that is currently undertaken. Current monitoring, where it exists, tends to be reactive (only occurring when a model related issue appears), ad-hoc and not consolidated across different model types across an institution. We will describe in detail our rationale for the need for CMM. Following this we will discuss some of the practical considerations necessary in order to incorporate and implement CMM into a model governance process (leveraging pre-existing testing where available). We believe that successful adoption of CMM would bring multiple benefits and efficiencies to all the stakeholders in the model governance process and we will highlight these at the end of the paper.

Ultimately an institution's motivation for implementing CMM should be the recognition that it is a crucial tool in using models safely, thereby leveraging their benefits to maximum effect for both shareholders and regulators.

Introduction

In a previous paper [PwC 1] we discussed the role of mathematical and computational models in the Financial Services (FS) industry. Our main conclusion in this paper was that the use of sophisticated models was on balance a positive factor for FS with a very important caveat. Namely that models should be used only when they are fully understood and in particular their fundamental limitations quantified. The role of Model Risk Management and in particular independent model review and robust challenge play a crucial role in this process.

In [PwC 1] we also introduced the concept of Continuous Model Monitoring (CMM) as a means of monitoring a model's performance throughout its working lifetime. In this paper we will expand on this concept explaining in detail why CMM is needed and how it can go beyond current best practice observed in the industry. Ultimately an institution's motivation for implementing CMM should be the recognition that it is a crucial tool in using models safely, thereby leveraging their benefits to maximum effect for both shareholders and regulators.

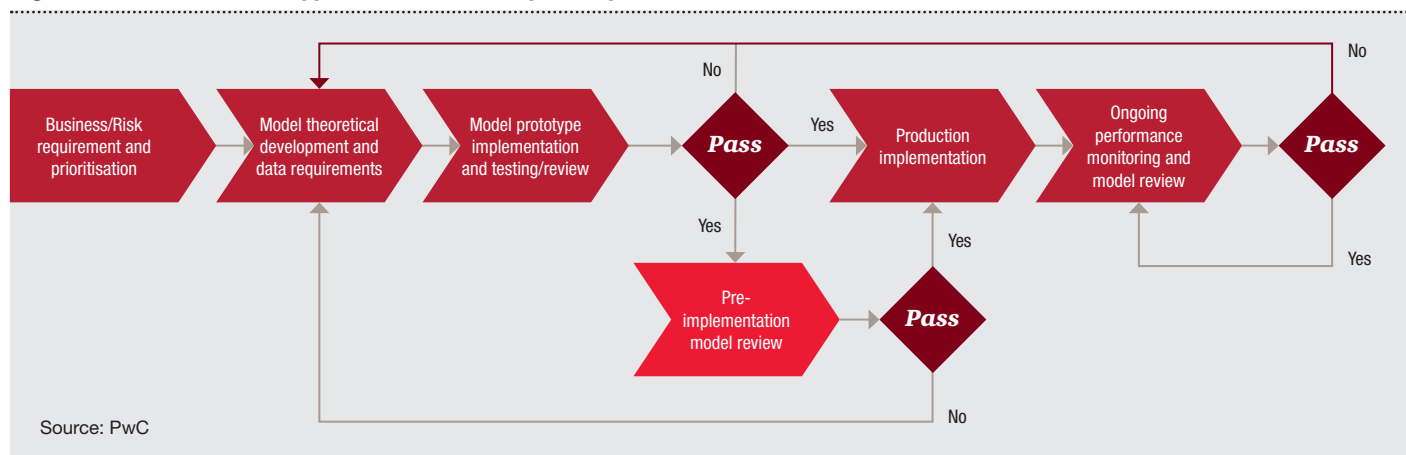
We will also describe in detail how we envisage an institution can embed CMM into its overall model governance process and discuss some of the practical difficulties that must be overcome.

The need for Continuous Model Monitoring

2.1 A typical Model Development/Governance Process

In Figure 1 we show schematically our view of a typical model development process.

Figure 1: Schematic of a typical model development process



The process begins with a business requirement for a new model. For example, a trading desk in an investment bank wanting to trade a new type of product for which no suitable valuation model exists, or in response to a new regulatory capital requirement. To meet this requirement, the relevant quant team will research and prototype what they believe to be a suitable model. During this period the quants will typically be testing their model's behaviour (including its implementation); in addition to this the traders or other model users will also be testing the model to see if it meets their requirements (as well as

doing their own sanity checks – in our experience traders can be quite effective in identifying if a model does not behave as they expect/want it to).

Once the quants and model users are happy with the model it will then be passed to Independent Model Validation, Risk Management and Product Control for their assessment. For example, in the case of a valuation model Risk Management will look to see if the model produces the risk sensitivities relevant to the product or purpose the model is used for. Product Control will assess what reserves must be held against known

User acceptance testing of the prototype will ensure acceptance of the underlying model while production acceptance will be concerned with data quality, controls and model integrity.

limitations of the model as well as factors such as withholding P/L due for example to unobservable parameters in the model.¹ Finally, Model Validation will undertake their independent assessment of the proposed model. Ideally Model Validation will leverage the testing undertaken by the Front Office. However it is important that Model Validation undertake whatever due diligence they deem to be necessary in order to independently assess the model and challenge the modelling assumptions and choices that have been made.

Assuming the model passes all the independent tests it will then be implemented in a production environment (often this implementation will be carried out in parallel – or before – the independent model testing). Testing of the production implementation against the prototype will be undertaken at this stage. User acceptance testing of the prototype will ensure acceptance of the underlying model while production acceptance will be concerned with data quality, controls and model integrity. Finally the model will be brought live in the production environment and used to produce actual ‘numbers’.

Thorough documentation of each of these steps should be produced, enabling all of the modelling choices and assumptions to be justified in a transparent manner. This documentation along with all the sign-offs should be part of the information captured in the model inventory.

The final step in the process is the ongoing monitoring of the model’s performance and periodic model re-review (typically as part of an annual review process) as the model moves through its working life. Often this re-review amounts to the following attestations:

- The model users reporting that the model is still in use and relevant for the financial products/ purpose it was designed for and that the model is still performing as expected e.g. no calibration failures due to current market conditions.

- Risk Management stating that the risk feeds produced by the model adequately capture the risk sensitivities of the product and the status of any Risks-Not-In-VaR (RNIV’s) (that is, risks that the model is known not to be able to capture).
- Finance giving their opinion on the adequacy of the current model reserves and the status of unobservable parameters.
- Model Validation confirming that any model conditions of use, limitations or weaknesses identified in the initial review have not been breached.

Ongoing monitoring of a model is necessary because a model developed at a particular point in time will reflect the market conditions at that time.² There is no guarantee that the same market conditions will prevail during the lifetime of the model.

The process described here applies equally well to all types of model. For example market risk (VaR) engines, counterparty credit risk (potential future exposure) engines (including CVA, DVA, FVA etc. calculations), regulatory capital models (Incremental Risk Charge, All Price Risk measure etc.), retail models and derivative valuation models would all have to go through the same basic process described, just with different stakeholders at each stage of the process.

All of these steps in the process form part of the overall model governance policies and procedures for the institution. Typically a committee formed of representatives of all the stakeholders in the model development process will manage the governance process, including prioritisation of model approvals and reporting of the status of models to the regulator. In our experience the details of the governance process differ from institution to institution in the precise detail, but the overall shape of the process is broadly common across the industry.

¹ For example, if a model has a parameter that is not observable in the market, Product Control may look at the sensitivity of the models output to variations in this parameter and compute an amount of P/L to withhold to mitigate against the desk marking this parameter incorrectly.

² A good example of this are models for interest rates which were developed in high-interest rate environments and are no longer applicable in the current low-interest rate environments.

2.2 What is wrong with this picture?

As discussed in [PwC 1], our view is that FS institutions have become very skilled at the initial assessment of models at the beginning of their working lives. Model owners perform extensive behavioural³ and implementation testing of their models. Independent model validation undertakes independent testing of the model (to verify the implementation of the model, the claims of the model owners as to the behaviour of the model and to assess the overall level of appropriateness of the model for its intended purpose). Very importantly, Model Validation seeks to challenge all the modelling assumptions and choices that the model owners have made.

Risk Management and Product Control also assess the model. In addition to this models are subject to assessment by Internal Audit. Quantitative model audit is typically focussed on testing the effectiveness of the controls – detective and preventative – in place around the usage of the model. It is undeniably the case that the level of scrutiny applied to models and model choices is far greater than a decade ago.

Additionally we note that FS institutions have made great strides in tracking the use of models across the entire institution (and not just on an individual model or trading desk basis as was the norm pre-crisis). The construction of model inventories listing information such as model owners, sign-off status, last review, model documentation etc., has been a huge step forward in managing model risk.⁴ We note in passing, however, that it is our view that these inventories in their current form are not nearly extensive enough in the information about models they capture, nor in how the information is used.⁵ Inventories tend to focus too much on descriptive

information and often do not contain either qualitative or quantitative information. There is also often a lack of time series information relating to model information in the inventory, making it difficult to track trends in evolution and usage.

Our fundamental hypothesis is that the model governance process described is generally quite robust but has one significant weakness; the ongoing model performance monitoring during a model's working lifetime.

In particular we believe that the ongoing performance monitoring is deficient for a number of reasons:

- The frequency of the process is too low to proactively identify emerging model issues (which could potentially lead to large losses) – in our experience markets can move very quickly to render modelling assumptions and choices invalid.⁶
- Where issues are identified (e.g. a calibration failure), quite often these are resolved in an ad-hoc manner by the model owners without recourse to the formal model governance process (particularly if the model owners can argue that the model change is 'immaterial'). This can lead to unmanaged model creep where a model's characteristics and behaviour gradually evolve over time, potentially invalidating the original approvals. Model creep should be captured as part of the annual review process, but by this time significant damage may have been done.

⁴ It should be noted, however, that in some large investment banks such efforts have been ongoing for years in one form or another.

⁵ In particular, we believe that there is the potential to mine the information in these inventories. What would be the outcome of such a mining exercise? Impossible to tell a priori, however it would be interesting to undertake the exercise to see what patterns and correlations between model performance emerged.

⁶ Or as the economist John Maynard Keynes observed 'The market can stay irrational longer than you can stay solvent' (When Genius Failed (2000), Roger Lowenstein).

Many institutions would argue that their current model governance processes are sufficient to catch problems with models as they occur.

In most banks, monitoring activities are at best ad-hoc and lacking any systematic approach across the institution.

- As a model evolves, it is more likely than not that the associated model documentation is not kept up to date, meaning that eventually there may be little relation between the current model implementation and its original description. Given the churn in resources within FS, important historical knowledge about the model can be lost (such as the rationale for a particular model change that occurred five years ago).
- The process is reactive; problems are only acted on once they have occurred and once they have been brought to the attention of the model governance committee.
- The process relies heavily on expert judgements and subjective analysis; it is often the responsibility of the model users (e.g. Front Office) to identify and report model issues. In some circumstances model users may prefer to make do and mend or find workarounds rather than address the problem properly (given that this may require a model to be temporarily taken out of use for an unknown period of time while the problem is fixed). Such an approach may only be storing up problems for the future.
- Given the business as usual workload of the stakeholders there is often little appetite for engaging in extensive re-reviews of models unless absolutely compelled to.
- An inefficient and ineffective model governance process may in fact be destructive to model risk management (leading to a false sense of security). This is because less attention is given to model issues as it is believed that these should be picked up through the governance structure that is in place.
- Without a dedicated team, any issues with the model may take so long to fix and implement that by the time the model is updated, there may already be other issues that it needs to be changed again.

To mitigate these limitations we propose enhancing the model governance process to incorporate a formalised Continuous Model Monitoring process. We believe that the introduction of this process can demonstrably mitigate the deficiencies identified earlier.

Many institutions would argue that their current model governance processes are sufficient to catch problems with models as they occur. Market risk analytics teams, for example, are certainly pro-active in monitoring the performance of their models.⁷ And in many banks, developers and users perform analysis for their own models and submit the results and conclusions to a model risk management function who in turn use these as part of an annual review process and for model risk reporting to governance committees and the board. An annual review process is too infrequent and too long a timeframe to sufficiently capture the required model updates.

However we would argue that such activities are often not performed at a sufficient frequency, lack the full breadth of testing required and rarely trigger the required actions. In most banks, monitoring activities are at best ad-hoc and lacking any systematic approach across the institution. It is precisely this systematic approach to model performance monitoring – that is also independent of the model owners – which we believe is the true value of CMM. It enables an institution to confidently and on an ongoing basis quantify and understand the model risks it is running (at least with the models currently in use).

⁷ This extends beyond back-testing to include activities such as statistical testing of the appropriateness of the scenario generation methodology.



2.3 What is Continuous Model Monitoring?

The concept of model performance monitoring is obviously not an original one. Indeed many different types of model have one form or another of monitoring. For example:

- Market risk VaR engines are subject to extensive back-testing to verify that the model is correctly capturing all the relevant risks (typically quantified by counting the number of exceptions where the model's performance is not good compared to the actual realised P/L's).
- Derivative models and trading strategies can be assessed using hedging simulation (similar to back-testing).⁸
- Stress testing can be used to assess a model's performance. For example, it is difficult to back-test the IRC regulatory capital model due to a lack of suitable historical data. In this case stress scenarios can be used to compare the model's performance against adverse scenarios.⁹

What we are proposing is something new – the formalisation of the model monitoring process into a separate function (team) independent of other model stakeholders. The remit of this team is to implement, execute and analyse model performance tests on a systematic, consolidated and ongoing high-frequency basis (typically daily).

⁸ Utilising the hypothesis that the value of a traded derivative should be approximately equal to the value of its hedging strategy.

⁹ In the case of stress tests, there is quite often an element of expert judgement required to specify the stress scenario.

By controlling the model's development in an evolutionary manner, we can hopefully avoid severe, discontinuous changes to a model necessitated by changes in the market environment.

Our hypothesis is that by constantly tracking a model's performance against specified metrics, we can identify emerging trends in a model's performance proactively. Such an early warning system can assist with the ongoing, controlled, evolution of a model as market conditions change. By controlling the model's development in an evolutionary manner, we can hopefully avoid severe, discontinuous changes to a model necessitated by changes in the market environment. Such discontinuous changes, because they are a reaction to changing market conditions, can often lead to significant mark-to-model losses.

In this view CMM is an extension of the daily regression testing that is typically undertaken on production code (e.g. tests on a random number generator). In this case however we are not testing the individual components of a model against errors in implementation (potentially introduced during ongoing code development); instead we are continually testing the performance of models against the evolving market conditions, and thus helping to manage the model risk. If we can quantify the operational envelope of a model (that is, the range of model/market parameters where we are confident that the model is suitable for use) then we can track the model's performance in relation to this envelope. In particular we can monitor the rate at which a model is approaching the limits of its operational envelope thereby providing an early warning signal of potential model issues.

The Fed OCC SR11-7 [Fed] supervisory guidance on model risk management, currently seen as the best practice standards to be adhered to for model development, provides guidance on the essential ongoing monitoring of a model to confirm it continues to perform as intended. This guidance includes details on the types of tests to be considered including internal and external data inputs, quality and change procedures of code, sensitivity analysis, benchmarking, analysis of overrides and more. It could be argued that all these tests are currently being undertaken on an ongoing basis under existing model governance frameworks in line with this guidance. However, it is the low frequency, lack of consistency and lack of consolidation of these tests across an institution that may result in inadequate model risk governance and ultimately potential losses. The SR11-7 guidance stops short of stating, for example, the actual frequency with which these tests occur, simply suggesting that it is appropriate to the nature of the model, the availability of new data or modelling approaches and the magnitude of the risk involved. We would argue that for many models the appropriate monitoring frequency is in fact continuous, or as near to continuous as can be realistically achieved.

2.4 How Does Continuous Model Monitoring fit into an existing Model Development and Governance Framework?

It is all very well proposing an additional stage in the model governance process. However it is not a very practical suggestion if it would require wholesale redesign of an existing process.

Fortunately, we envisage CMM as integrating naturally into the existing model governance process. In terms of process, CMM would begin once a model has received its initial approvals and has been implemented into a production environment and has gone live producing numbers for daily P/L, regulatory reporting or other business decision-making activities. We observe that the CMM function is independent of the other model stakeholders (in the same way that Model Validation is independent of the model owners).

The aim then would be to implement the CMM process for this model within, say, the first year of the model's use.¹⁰ Once CMM has gone live the results of the ongoing model testing will be distributed on a daily basis to all the model stakeholders. Summaries of the results, in particular issues of concern identified by the continuous testing, can be integrated into the model reporting process. Indeed, it is easy to see that the output from CMM could be used to report on model performance to the regulators.¹¹ The appendix contains a sample of the type of reporting that might be possible.



Once CMM has gone live the results of the ongoing model testing will be distributed on a daily basis to all the model stakeholders.

¹⁰ We are making the implicit assumption that once a model enters production use it will not immediately become invalid. The grace period of one year recognises that it will take time to implement a robust CMM process even for the simplest models.

¹¹ This already happens for some models. For example the results of VaR back-testing analysis are routinely communicated to the regulators.

Implementing Continuous Model Monitoring

In the previous section we described why a process like CMM is needed in order to manage model risk most effectively. In order to understand the challenges faced in implementing CMM as well as its benefits, it is instructive to go through the practical steps that would be necessary in order to incorporate CMM into an existing model governance framework.

3.1 What is the scope and remit of the CMM team?

To execute CMM we propose that a separate team be put in place, whose sole remit is to run the CMM process. Given the scope of the task, it would not be feasible to place the responsibility for this on the Model Validation or other quant teams. CMM could feasibly be run by either of these teams, but we believe that the CMM process should be executed independently of the business or model owners in order to maintain confidence in the independence of the CMM process. Equally important, placing the responsibility for CMM with a dedicated team emphasises the importance of the function to overall model governance as well as ensuring that CMM does not get relegated behind other BAU tasks.¹²

Specifically we would expect the CMM team to:

- Be represented on the model governance steering committee to provide periodic updates on ongoing model performance and any other issues arising from the execution of CMM. Additionally the CMM representative would also participate in the annual review process (indeed the input from the CMM team would substantially influence this process).
- Work with the rest of the model governance stakeholders to prioritise implementation of CMM for individual models/products (the Model Inventory can be used to guide these decisions).
- Be responsible for the design and implementation of the tests and metrics used to monitor a model's performance (with input from other stakeholders).
- Be responsible for the documentation of the test rationale etc.

¹² It is difficult to imagine Model Validation having the resource requirements to effectively manage the CMM process. Therefore there is always the danger that CMM tasks would be de-prioritised in favour of the 'day job'.

- Be responsible for the first line-of-defence verification of the implementation of the tests.
- Be responsible for the day-to-day running and analysis of the CMM tests (including potential data mining of the database of historical model tests with the aim of uncovering potential model dependencies and correlations hitherto unobserved).
- Be responsible for the day-to-day communication of the CMM test results to the relevant model stakeholders.
- Be responsible for the escalation of potential issues to the appropriate stakeholders.
- Be responsible for evaluating the impact of issues identified and making recommendations for resulting actions.
- Take ownership for the ongoing maintenance and development of the Model Inventory (MI).

The design and implementation of the CMM tests is clearly a crucial role of the CMM team. Because each model is different, we do not believe it is possible to define a one size fits all approach to the design of the CMM tests. Each model will have to be considered on an individual basis. This is a task that could also be supported by the other stakeholders in the model governance process, leveraging their knowledge of the model.

For example, Model Validation as part of their assessment, will undertake tests of the model's behavioural characteristics; an example would be stressing the model's input parameters to determine where the model fails, defining the so-called model operational envelope discussed in [PwC 1]. Part of Model Validation's conclusions should therefore include recommendations as to what tests would be necessary for thorough and robust CMM.

In addition to behavioural tests, Model Validation may also implement an independent version of the model (to test for implementation errors that behavioural tests may not detect), or indeed an alternative model to try and quantify the model risk associated with the choice of model. As part of the CMM tests, it may also be beneficial

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to implement such an alternative model whose ongoing performance could be compared against the model in production. Clearly the precise nature of the CMM tests will be dependent on the particular model in question.

Additionally, it will also be important to independently validate the implementation of the CMM tests, as well as independent verification of the sagacity of the proposed tests of a model's performance.¹³ It is proposed that the CMM team will perform first line-of-defence independent tests of the implementation. These tests ensure the accuracy of the implementation. We also advocate that the CMM team document the model tests they propose (purpose and rationale of test, required data, frequency of run, expected results, what a fail looks like, trigger levels for escalation etc.). It is proposed that during the design phase of the tests, the CMM test documentation be circulated to the model owners and other stakeholders for their assessment; suggestions and recommendations should be incorporated into the CMM test design where appropriate (leveraging the deep knowledge that the model owners will have of their models).

The CMM team's interactions with other stakeholders in the existing model governance structure would be a two-way process. As described, it is clear that Model Validation would help drive decisions over the nature of some of the tests covered. However, in addition stress testing and back-testing teams may also provide guidance on tests in these areas and product control may provide information on required tests relating to model reserves. The results of the ongoing monitoring by the CMM team would in turn drive the work of other stakeholders. For example, the results of certain tests may trigger model validation re-reviews, model rebuilds by quant developers or even an internal audit review.

¹³ The proposed model tests must make sense from a business perspective as well as from an implementation perspective.

We also advocate that the CMM team take ownership of the Model Inventory. This would allow the CMM team to assess what models require the implementation of CMM and to determine recommendations for implementation prioritisation going forward. Crucially however, we believe the CMM team would, by the very nature of the work they undertake, be able to develop a deep understanding of the type of information that should be captured in the inventory. In particular we believe that simply capturing simple descriptive data, such as the model owner or date of last review, underestimates the potential power of a Model Inventory. Leveraging the concept of a Model Inventory further would facilitate deeper analysis as to potential correlations and linkages between model performance that may not be immediately apparent.

Finally we note that the remit of the CMM team is not to provide review and challenge of a model. This function is undertaken by Model Validation. The role of the CMM team is to monitor that the model that is put into production is being used as it was intended to be and is within its established operational envelope.

All of these requirements for the CMM team should be encapsulated in a CMM team operating manual outlining the policies and procedures for the team's operation.

3.2 What would be the resource requirements of a CMM team?

On a positive note, once CMM has been set up for a particular model the ongoing running of the tests is a fairly automated process.

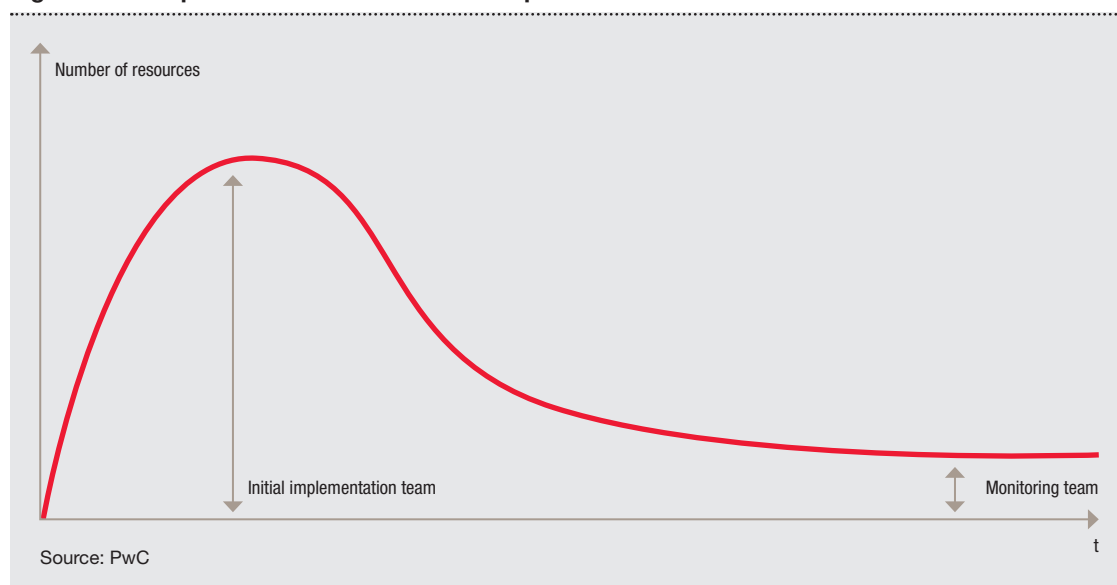
To implement CMM for a particular model from scratch requires a good deal of understanding of the model (although as noted above it is anticipated other stakeholders with knowledge of the model can also contribute to the CMM design). Knowing what characteristics of a model need to be monitored, how to construct relevant metrics and how to implement these is a potentially difficult task, particularly for complex models. In addition to this the detailed analysis of a model's test results will also require a good deal of expertise and experience. Therefore the CMM team will require a number of individuals with substantial quantitative experience.

While the initial requirements for setting up a CMM team may seem to be daunting, it may not be quite as difficult as it first seems. Many of the tests required will be currently undertaken in different teams within the Risk and Finance areas of a bank albeit at a different frequency and with differing levels of granularity (and almost

certainly no consistency or consolidation between the different tests being undertaken). A large part of the initial work required to set up the CMM team may in fact be to identify where processes already exist and can be coordinated into a centralised function. The recently introduced regulatory requirements around stress testing are a good example of where sophisticated financial institutions have had to rapidly consolidate information across many different businesses into a single coherent process.

On a positive note, once CMM has been set up for a particular model, the ongoing running of the tests is a fairly automated process. What would be required is monitoring of the test results with subsequent drill down into any which are demonstrating unexpected behaviour (we would also advocate frequent random spot checks of test results just to be sure that things are running as expected). These tasks could be undertaken by relatively junior analysts (with guidance from

Figure 2: Anticipated CMM team resource requirements over time



Over time as the CMM framework become bedded in and reaches a steady state the number of resources could be decreased until eventually we are left with a core monitoring team.

senior analysts). Indeed, running and analysing these tests would be a good training environment for junior analysts as they would quickly become very skilled in analysing and understanding model behaviour.

In terms of the numbers of resources we would speculate the following as a representative scenario:

- Starting from scratch (with no CMM implemented for any models) we would expect to require a number of experienced resources (approximately one for each asset class/model type¹⁴). These resources would begin by assessing the model testing already undertaken across the institution and based on this set out the implementation plan for the first stages of CMM (with the model prioritisation set out by the model governance committee).
- More junior resources would then be required to implement the CMM plans (with guidance from the senior resource) – the precise number of junior resources would depend on the institution's appetite for implementing the CMM process as quickly as possible (this is the implementation team in Figure 2).
- Over time as the CMM framework becomes embedded and reaches a steady state the number of resources could be decreased until eventually we are left with a core monitoring team.¹⁵

¹⁴ For example a sophisticated financial institution may have subject matter experts (SMEs) for Market Risk, Credit Risk, Reg Cap models, equity derivatives, rates derivatives, FX derivatives, credit derivatives and commodity derivatives. As is the case in typical Model Validation teams, each SME may have two to three specialisms (with support from other resources as required). Hence we believe that of the order of five SME's would be sufficient for the initial ramp-up phase of the CMM function.

¹⁶ Indeed the responsibility for the steady state day-to-day running of the process could be outsourced either to a low-cost offshore centre or external contractors. As model issues are identified they would then be communicated back to the model owners.

Because the CMM process is a highly technical one from a computational point of view, we also recommend that the CMM team would require a dedicated technical support analyst. The role of this individual would be to develop (with the quants) the initial implementation of the CMM engine (see later), maintain the smooth running of the scheduled tests, administration of the testing results database, liaison with other IT teams (for example Front Office IT) and other ad-hoc IT-related tests to support the quants in the analysis of the models.

Finally, we also recommend a CMM team leader. This should be a highly experienced individual with a broad range of model experience across a wide range of different model types. The team leader will also require the inter-personal skills necessary to manage the team and interact with other senior stakeholders in the model governance process.

3.3 What would the day-to-day activities of the CMM team be?

We have identified what the CMM team will be expected to do in terms of the big picture and who would be in the team. But how does this translate into in terms of their day-to-day activities. We anticipate that the day-to-day activities will include:

- Making sure that all the CMM tests are running as scheduled.
- Investigating instances where the tests fail. Is the failure due to an IT issue (e.g. lack of market data because a feed failed), an implementation error in the test harness¹⁶ or, most seriously, a model failure?
- Detailed analysis of the CMM tests (not perhaps a daily task, but one which would be undertaken on a regular basis).
- Performing random spot checks and analysis of the results of the tests to verify accuracy.
- Population of the CMM Model Risk Dashboard for the day's tests.
- Circulation of emails of the test results to the model owners and other relevant stakeholders.
- Escalation of potential issues to the relevant stakeholders (for example, using a RAG traffic-light system).
- Liaise with stakeholders to ensure that issues are looked at and resolved.
- Design and implementation of CMM tests for those models not yet covered by the process.

¹⁶ In our experience, the test harness and how it integrates with the production model will be a potential source of many unexpected errors e.g. 'stale handles' in a spreadsheet.

3.4 What would be the Output of the CMM team?

The primary daily output of the CMM team will be the CMM Model Risk Dashboard (MRD). An example of the type of output that could be produced is shown in the appendix. This will be a report with a separate entry for each model for which CMM is implemented. Each entry will provide a summary list of the tests undertaken and the results of the test e.g. Pass/Fail with additional commentary as required. Where appropriate, graphs and other optics of the historical performance of the model will also be provided (for example a graph showing the evolution of the distance of a model from the limits of its operational envelope). The dashboard will be sent daily via email to the model owners and other relevant stakeholders. The expert judgement of the model owners should also be sought as to the interpretation of the test results (where this is not obvious).

The MRD in its simplest form can provide information on a particular model's performance. However, more intriguingly, in addition to listing individual model performance, the MRD can also introduce performance metrics capturing higher-order dependencies between models. For example, if two models being used in disparate parts of the institution are simultaneously displaying signs of poor performance (although not yet technically failing the tests), is this due to a set of common modelling assumptions that are being rendered invalid under current market conditions? Or is the simultaneous deterioration in performance simply down to random, uncorrelated events? In this way, the MRD is a significant step up on most existing reporting of model risk.

One of the biggest sources of losses in the financial crisis was down to the simultaneous convergence in correlated behaviour across many different market variables spanning multiple asset classes (including variables that had previously shown little historical correlation). This led to all manner of simultaneous performance issues with models (ranging from synthetic CDOs failing to calibrate due to increased systemic risk, to interest rate models failing because base rates were being slashed in response to the demise of systemically important financial institutions). This is an extreme example, but as history demonstrates an entirely plausible one. The current model governance framework (which is typically organised along the lines of asset classes) would struggle to observe the behaviour of two models in different parts of the institution, let alone multiple models across many parts of the institution. However the CMM team would be able to identify this behaviour relatively easily because it is the CMM function's *raison d'être*.

In terms of output, an overall long-term goal for CMM might be the development of an aggregate metric that quantifies the overall model risk the institution is running at any point in time. For example a Model-at-Risk (MaR) number (analogous to Value-at-Risk for quantifying market risk). Taking this idea further, it is not hard to envisage a situation where the MaR number is reported daily to regulators and board members (where the Chief Model Officer has the responsibility for quantifying and managing the institution's model risk). Quantification of model risk should become as commonplace as quantification and reporting of other types of risk that institutions are subject to, such as market risk and credit risk.

In terms of output, an overall long term goal for CMM might be the development of an aggregate metric that quantifies the overall model risk the institution is running at any point in time.

3.5 Reporting and escalation of Model Issues

The output of the CMM tests will provide an indication of when a model's performance may be moving into an area of concern (moving towards the limits of its operational envelope). Where this is observed, this will be specifically flagged in the daily email to the model owners. The model owners will be required to investigate the issue and report back on a resolution of the issue within an agreed timeframe.

All such issues identified will be recorded in a CMM Model Issue log (potentially as part of the model inventory). The issues log will be part of the CMM team's reporting requirements to the model governance committee.

3.6 What would be the Technical Architecture for the CMM Process?

Finally, we consider the technical architecture of the CMM process. Figure 3 shows schematically how the CMM function would be implemented. At the heart of the system is the CMM engine. The engine integrates all the market and position data (which is marshalled in its own separate staging area) with the production implementations of the models and the CMM test suites for each model. The purpose of the engine is to take all this information, run the tests and write the test results out to a database for subsequent storage and analysis (as well as reporting test failures). The engine will also handle all of the scheduling of the test runs (not all tests will be run at the same frequency) on a systematic basis.

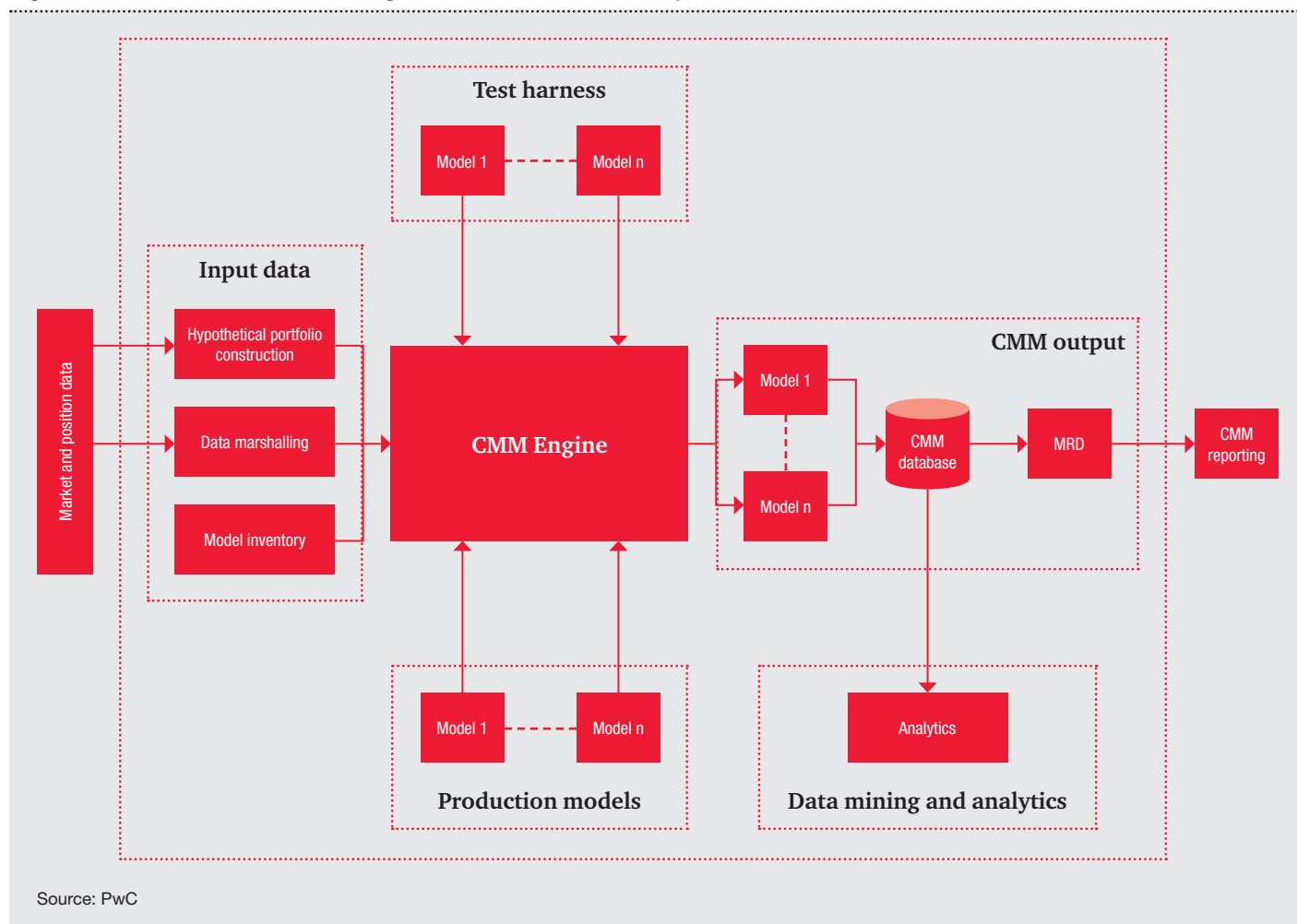
It is anticipated that the CMM function would be implemented in a separate IT environment that leverages the existing production environment for the models (for example in the same way that VaR engines leverage the production model analytics). Specifically the data requirements for CMM (market data, position data etc.) would be sourced from the same systems that feed the production implementation of the model. This has the advantage that the input data to the CMM tests is subjected to the same level of cleansing

and validation as that used for the production runs of the model.

The actual tests would be implemented in an environment such as a spreadsheet (used as a test harness). The output of the tests would be written out to a database. A database is necessary to store the results of multiple tests run on many different days. It is not feasible to use a spreadsheet as a repository to store the historical test results (necessary for tracking the models' performance over time) due to the volume and complexity of data generated, particularly once the CMM function reaches a steady state. The information stored in the database would be used to produce the Model Risk Dashboard which is sent out to the model owners on a daily basis. The database would also be used to undertake ad-hoc analysis of historical model performance data where appropriate.

Figure 3 also shows a function for constructing hypothetical portfolios. Hypothetical portfolios are necessary if we wish to track the performance of certain types of model over time (which we clearly do). For example, if we are monitoring the performance of a regulatory capital model,

Figure 3: Schematic of the technological architecture for the implementation of CMM



such as the Incremental Risk Charge (IRC) model we need to have a constant underlying portfolio which the tests are applied to on a daily basis; if the portfolio were not constant then it would not be possible to compare the models output as a result of different test runs.

This is in contrast to the situation where we want to track the performance of, for example, an individual derivative valuation model (such as the ISDA Credit Default Swap model). In this case we will typically specify a single position (not a portfolio) with constant trade economics (e.g. the trades maturity does not decrease in time) to analyse. This example would not need a hypothetical portfolio in order to track the models performance over time.

Also shown on Figure 3 also shows data mining and analytics capability. This takes as input the (historical) output of the CMM tests. As noted earlier it is our view that CMM will generate significant insight into the correlated patterns of model usage across an institution (the more sophisticated the institution, the more potential information to mine). As the CMM function embeds itself within the overall model governance framework, we would recommend

It is possible that there are correlations between drivers of model risk that have so far been unidentified with potentially significant consequences.

investing effort in trying to understand emergent patterns and dependencies in the CMM output; the results may be eye-opening. It is possible that there are correlations between drivers of model risk that have so far been unidentified with potentially significant consequences. Furthermore, the sheer number of unidentified, unnoticed issues would become clearer with this type of continuous monitoring.

Finally, we also include the Model Inventory in this picture. As noted earlier our view is that the Model Inventory should naturally reside with the CMM team as this will enable the CMM team to understand what models are in use and therefore require CMM implementation. In addition to this, and in concert with any insight into the aggregate model behaviour at an institutional level that the data mining unearths, the results of the CMM tests can also be used to understand what additional information would be beneficial to capture in the Model Inventory.¹⁷

¹⁷ For example, if two models simultaneously begin to deteriorate in their performance it may be the case this is due to common – previously untracked – assumptions. It would therefore make sense going forward to record the models assumptions in the Model Inventory.

What are the tangible benefits of CMM?

The practical steps we have suggested, which are required to set up and incorporate CMM into an existing model governance framework, require significant investment in resources and infrastructure. This raises questions as to the real benefits of undergoing such a transformation to the way that Model Risk is managed. We argue that the benefits far outweigh the costs, particularly in the future once the CMM framework is established. The benefits also impact all the different stakeholders in the model governance process.

4.1 Benefits to the overall Model Governance Process

An effective CMM function would assist in streamlining the model governance process in a number of ways:

- It could reduce the requirement for the attendance of a large number of senior people at periodic governance meetings. As problems on specific models would be clearly identified and flagged prior to the governance meetings, only those relevant stakeholders would be required to attend.
- As part of the model governance process, quarterly packs detailing model performance are typically submitted to the regulator (e.g. summarising regulatory backtesting of the VaR model). The production of these packs can be an onerous process, but the necessary information could relatively easily be an automated output from the CMM team (indeed, the MRD is just an example of this).
- Under a typical model governance structure currently in place, tests are undertaken by various teams such as Model Validation, Stress Testing, and Product Control in different parts of the bank. Also, full model reviews are conducted periodically, usually triggered by the time of the last review and not a specific need to review. This may result in time spent on a review where it may not be needed. CMM would allow for efficiencies resulting from tests being conducted in one place and re-reviews being triggered by specific information on poor model performance.

4.2 Benefits to the model owners and model users

For the model owners and users, the constant independent monitoring of their models by an external function would remove this responsibility from them. It would also help them identify potential issues with more foresight, enabling action to be taken before a problem materialises.

4.3 Benefits to Model Validation

As noted, Model Validation should provide recommendations as to what model characteristics need to be monitored. Once implemented by the CMM team this would remove any requirement for the Model Validation team to actively track these for breaches of the conditions on which the model is approved.

Additionally, requests for re-reviews would also be precisely targeted on those models displaying poor performance (rather than prioritising re-review on the basis of, for example, the time since the last review). This would ensure Model Validation resources are efficiently targeted where they are most needed. Indeed re-reviews could be prioritised over existing BAU work if the quantitative results of the CMM are sufficient to warrant this.



4.4 Benefits to Risk Management

Risk Managers may also want to set up hypothetical portfolios or other such specialised examples to monitor certain aspects of business performance.

From a Risk Manager's point of view, ongoing model performance metrics are a useful quantity to have and will help inform their decisions as to the risks a business is running. For example, if the model with the most exposure against it is starting to demonstrate performance difficulties it is necessary to know this as soon as possible.¹⁸

In addition to this, Risk Managers may also want to set up hypothetical portfolios or other such specialised examples to monitor certain aspects of business performance (for example how would the risk profile of the desk look given a change in risk appetite e.g. a different concentration of positions in the portfolio). Such hypothetical examples could be set up by the CMM team to provide ongoing monitoring information to the Risk Managers.

Having this information provided automatically on a systematic basis would facilitate more proactive risk management and free up the Risk Manager from having to try and determine this information for themselves.

Finally, by constantly tracking a model's performance against specified metrics, we can identify emerging trends in a model's performance proactively. Such an early warning system can assist the Risk Manager with the ongoing, controlled dynamic quantitative risk management of a model as market conditions change.

4.5 Benefits to Finance

CMM could assist Product Control in determining appropriate levels of dynamic model reserves. For example, if a model is operating far away from breaching limitation X, then the reserve for limitation X can be reduced; conversely if the model is approaching its operational envelope then the reserve should be increased. As part of their initial assessment of a model, Product Control could recommend what tests should be implemented to actively track the adequacy of reserves. In addition to this, the ongoing CMM may identify additional model limitations that were not initially considered for which additional reserves would be required.

The dynamic management of reserves in this way may potentially improve the profitability of the bank without compromising its risk management (by adjusting reserve levels in response to dynamic model performance).

¹⁸ Many Risk Managers take for granted the performance of models. In our view this is a dangerous assumption to make. We believe that a robust assessment of risk should take into consideration not just the positions in a portfolio, but also the models used to value these positions.

4.6 Benefits to Internal Audit

Quantitative model audits are becoming an increasingly important part of the model risk governance process. CMM output would provide quantitative audit teams with historical ‘evidence’ as to the performance of the model. In principle Internal Audit could also design tests (implemented by the CMM team) to monitor the ongoing effectiveness of controls (detective

and preventative).¹⁹ This would all lead to more effective audits and more effective use of quantitative audit resource (since the results of the audit related CMM tests would be readily available to the audit team).

4.7 Benefits to Market Risk (VaR) Analytics

As noted earlier, Market Risk Analytics teams are typically active in monitoring their models. This can be a time-consuming and resource intensive task. With sufficient thought it would be possible for the Market Risk Analytics team to design CMM tests to monitor certain aspects of the VaR models performance (for example, back-testing performance against a hypothetical portfolio, assessment of RNIV's, scenario generation methodologies etc.).

Once implemented by the CMM team, this would remove the responsibility for the ongoing running and analysis of these tests (reducing the workload on the VaR team). For example regulatory back-testing reporting could in principle be run by the CMM team (with the VaR team reviewing the results before signing off on them).

We also note that regulatory capital models, such as VaR engines, are constantly evolving as the market conditions change. However some changes to the model, such as changes to model parameters etc., usually require permission of the regulator, which requires large of amounts of quantitative analysis to be undertaken to justify the change. CMM would support this process by providing at almost no cost the evidence for the requirement for the proposed model change (although it would not inform about the proposed solution which would require the research effort of the VaR team).

As circumstances require, the VaR team would introduce additional tests into the CMM suite. Over time the responsibility for the monitoring of the entire VaR model would eventually reside with the CMM team, leaving the VaR team free to develop improvements and enhancements to the model.

With sufficient thought it would be possible for the Market Risk Analytics team to design CMM tests to monitor certain aspects of the VaR models performance

¹⁹ For example tests to monitor for discontinuous changes in model output due to an unauthorised change in model parameterisation.

Conclusions

In this paper we have argued that the current best practice in model risk management is deficient in one important respect; the ongoing monitoring of a model's performance during the course of its operational lifetime. In order to resolve this weakness we propose to introduce into the governance process, Continuous Model Monitoring (CMM). CMM is the formalisation of the model monitoring process into a separate function (team) independent of other model stakeholders, whose remit it is to implement, execute and analyse model performance tests on a systematic, consolidated and ongoing high-frequency basis (typically daily).

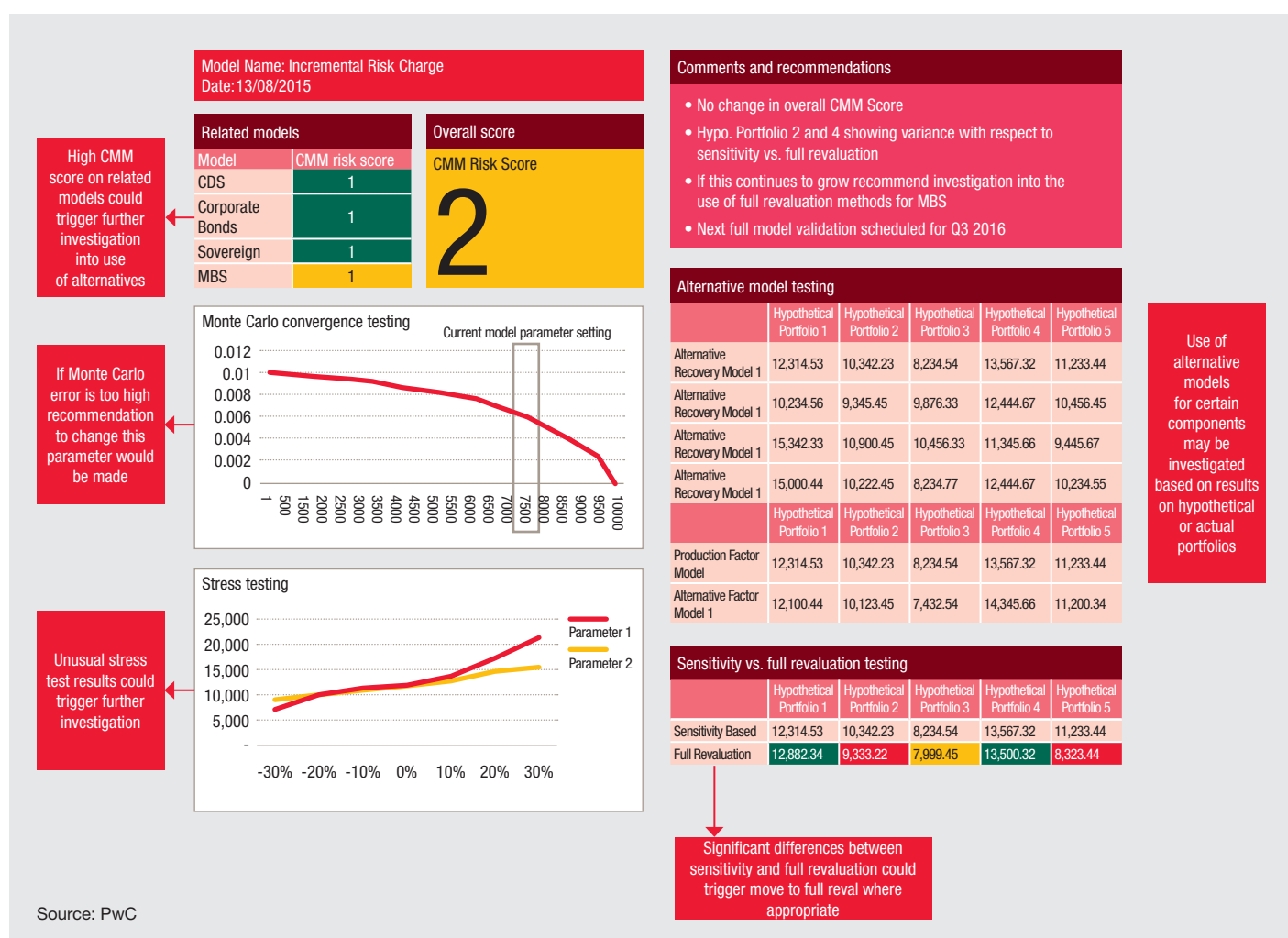
Our core hypothesis is that by constantly tracking a model's performance against specified metrics, we can identify emerging trends in a model's performance proactively. Such an early warning system can assist with the ongoing, controlled, evolution of a model as market conditions change (removing the need for potentially costly discontinuous changes to models).

In our opinion the benefits of CMM are manifold and can enhance the strength and effectiveness of the model governance process for all the stakeholders in the process. CMM brings together all the ad-hoc model performance testing performed across an institution into a consolidated framework that can be extended to provide additional insight into model behaviour and, importantly, correlations between model behaviour. There is significant potential to gain insight into large-scale model behaviour that is simply not possible to observe within the current framework.

We have also outlined the practical steps we believe are necessary in order to integrate CMM into an existing model governance framework. The initial effort to implement CMM will be significant (but not onerous), but in our view the benefits to all the stakeholders in the model governance process will far outweigh the costs and risks involved. In particular by leveraging the existing model testing that is currently undertaken, we believe that it would be feasible to implement CMM even for the most sophisticated financial institutions. In a separate paper we will present a number of case studies demonstrating the practical steps necessary to implement CMM for a range of representative models that a financial institution may be using.

Appendix:

Example of part of a CMM Model Risk Dashboard and the related actions that could be triggered



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