Formula 1 and the class of 2022 – bouncing cars and what it means in terms of digital twins and the validation of engineering simulation

Steve Howell – 20 September 2022

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Dr Steve Howell

Steve studied in Newcastle upon Tyne and is a chartered engineer. He has 25+ years experience in the application and development of CFD, founding Abercus in 2010 to provide specialist simulation and modelling services, initially to the energy sector.

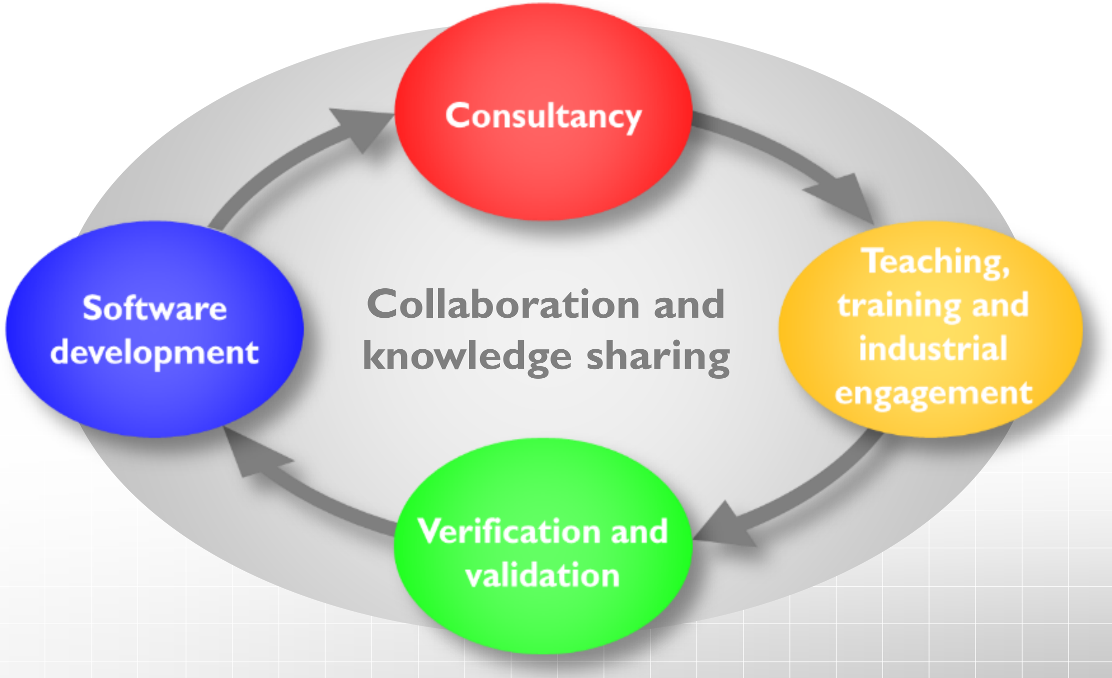
Steve is an active member of the CFD (Chair) and SGM* working groups at NAFEMS, the international organisation for engineering simulation.

Disclaimer: Neither Steve nor Abercus has any professional involvement in Formula 1 and this presentation is based largely on his observations of the porpoising issue as it has emerged in the media earlier in 2022, and through subsequent discussions with other individuals closer to F1. This material reflects his own thoughts and may not reflect those of the respective NAFEMS working groups.

* Simulation governance and management

Abercus

Abercus is an **independent**, privately-owned consultancy specialising in **advanced engineering simulation** – CFD, FEA, bespoke software tools and teaching/training.


Consultancy

Teaching, training and industrial engagement

Verification and validation

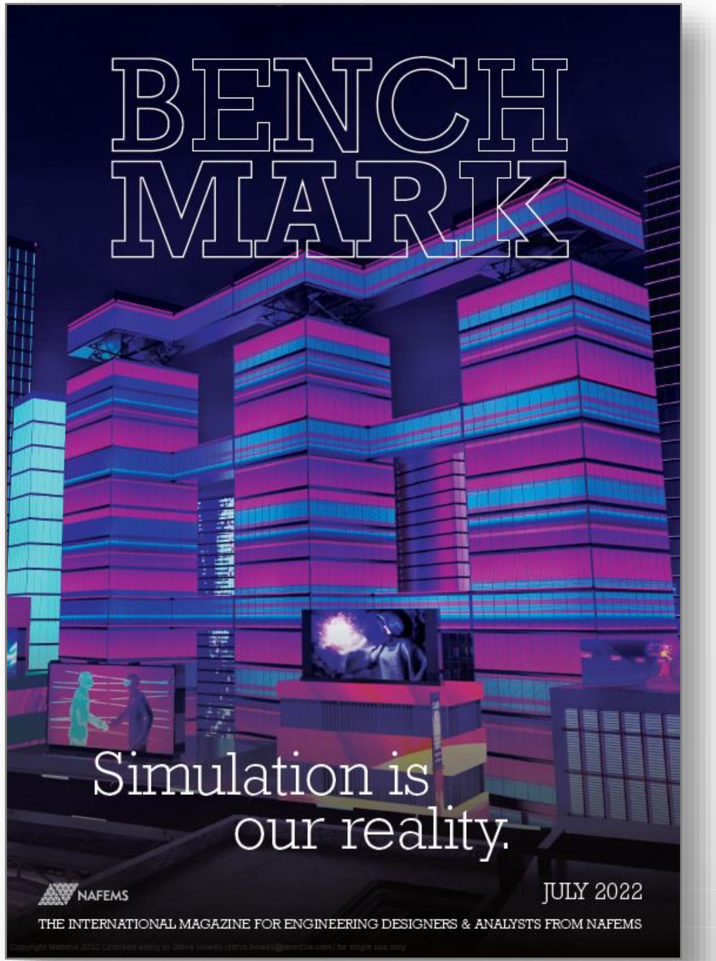
Software development

Collaboration and knowledge sharing

Agenda

- Porpoising and ground effect cars
- The class of 2022
- First on-track testing following the 2022 rule changes
- A framework for verification and validation
- Confidence in engineering simulation and the importance of abstraction validation
- Learnings from the bouncing F1 cars episode
- What this means for the wider application of engineering simulation
- Improving confidence through blind benchmarking
- The practicalities of the abstraction process
- In conclusion

Agenda



BENCHMARK

Simulation is our reality.

NAFEMS

JULY 2022

THE INTERNATIONAL MAGAZINE FOR ENGINEERING DESIGNERS & ANALYSTS FROM NAFEMS

nwc2021
NAFEMS WORLD CONGRESS
A WORLD OF ENGINEERING SIMULATION
INCORPORATING
spdm INTERNATIONAL CONFERENCE Simulation Process & Data Management
Multiphysics Simulation Conference

On the importance of abstraction validation for fluid flow applications

Steve Howell (Abercus)

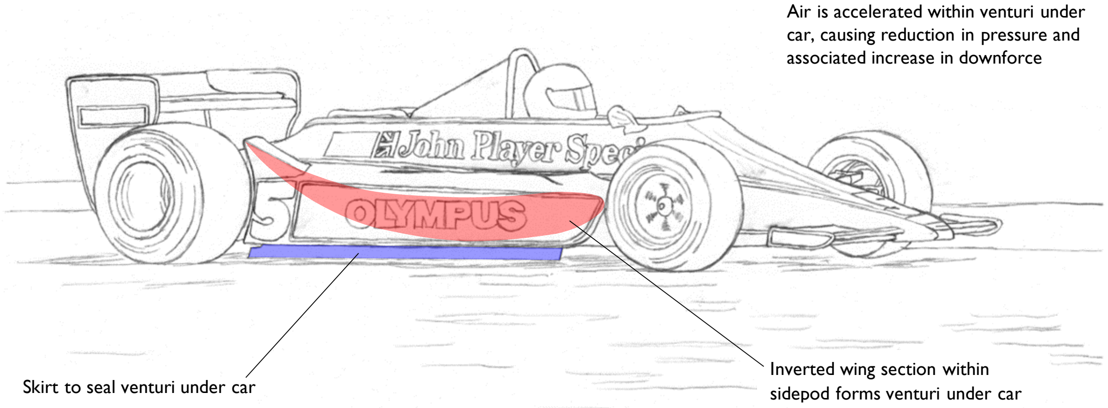
NAFEMS World Congress 2021

* Please email me at steve.howell@abercus.com for a copy

Porpoising and ground effect cars

- Porpoising is a rocking motion experienced by a car when it is travelling, due to repeated changes in the downforce experienced by the car.
- Porpoising is well known to be a issue for so called *ground effect* cars, and they were banned from Formula 1 on safety grounds in 1983.
- Since then, all F1 cars have been required to have a flat bottom – until the 2022 season, that is!

Concept for ground effect cars



The underside of the car is shaped to form venturi tunnels, to reduce the pressure between the car and the road surface, thereby increasing downforce and grip to improve cornering.

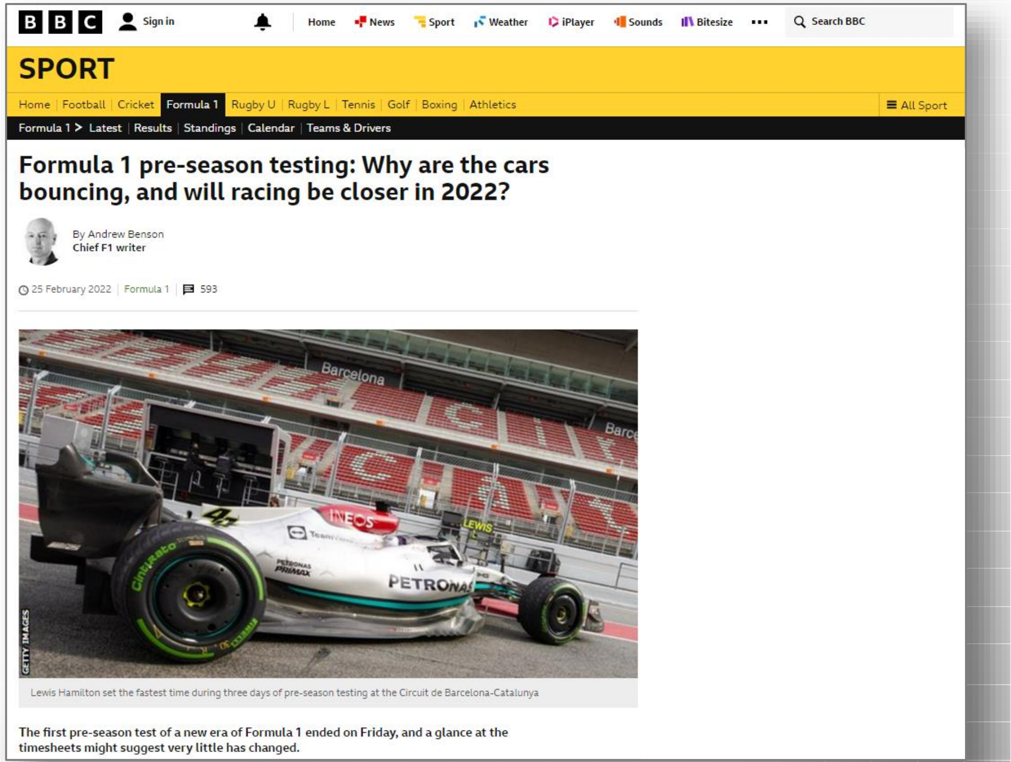
The Lotus 78 and Lotus 79 were the first cars to use ground effect to dominate Formula 1 – they enjoyed great success in the late 1970s.

The class of 2022

- In an effort to promote closer racing, the FIA has allowed F1 cars to once again exploit ground effect starting from the 2022 season.
- With the advances in wind tunnel modelling and computational fluid dynamics (CFD) since the early 1980s, the tools available to the F1 teams can now provide a significantly improved understanding of the aerodynamic performance of the cars.
- Indeed, the aerodynamics for the 2022 cars will have been entirely developed using a combination of CFD and wind tunnel testing, since on-track testing is not allowed under F1 rules until around one month before the first race of the season.
  - This is an approach that has evolved over the years, where confidence in CFD predictions is supported and validated though comparisons with corresponding wind tunnel data and on track data from previous seasons.

First on-track testing following the 2022 rule changes

- The first on-track testing took place during the last week of February 2022 in Barcelona, and it was quickly discovered that along with ground effect, porpoising had returned to F1.
- Despite the use of wind tunnels and advanced CFD, the risk of porpoising had not been addressed during the pre-track testing, so all of the teams were caught by surprise in Barcelona.
- This provides an important learning opportunity in relation to the validation of engineering simulation.



Formula 1 pre-season testing: Why are the cars bouncing, and will racing be closer in 2022?

By Andrew Benson
Chief F1 writer

25 February 2022 | Formula 1 | 593

Lewis Hamilton set the fastest time during three days of pre-season testing at the Circuit de Barcelona-Catalunya

The first pre-season test of a new era of Formula 1 ended on Friday, and a glance at the timesheets might suggest very little has changed.

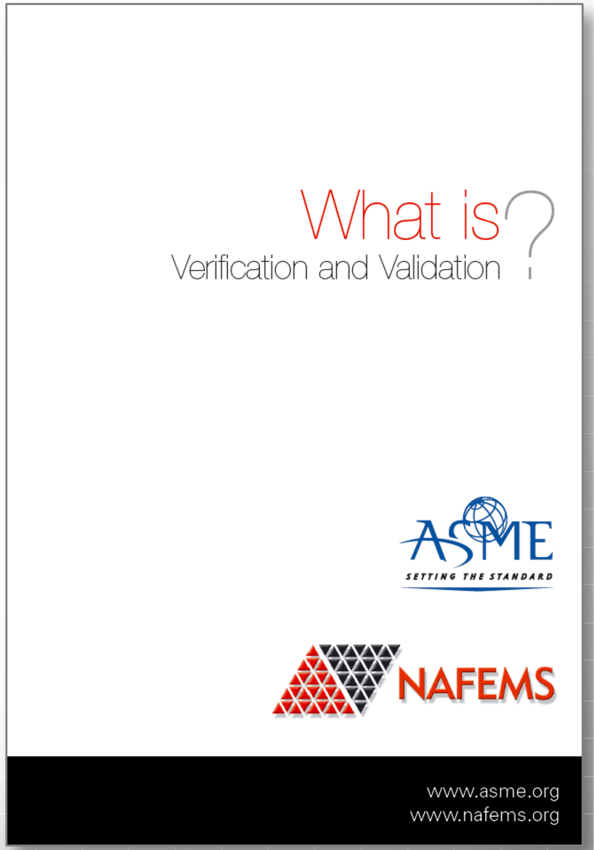
Background to initial issue: https://www.bbc.co.uk/sport/formula1/60522496.

Videos of bouncing cars in February: https://www.youtube.com/watch?v=NgPd9bCYX3w
(Go straight to 0:36 and 2:00 to see the Ferrari cars bouncing along the track.)

A framework for verification and validation

ASME V&V 10 diagram

- ASME and NAFEMS have published a *What is?* guide that is freely available for download:
  http://www.nafems.org/publications/browse_buy/browse_by_topic/qa/verification_and_validation/
- NAFEMS has also published the Engineering Simulation Quality Management Standard (ESQMS), which interprets quality standard ISO 9001:2015 in the particular context of the engineering simulation process:
  https://www.nafems.org/publications/resource_center/esqms-01/



What is?
Verification and Validation

ASME
SETTING THE STANDARD

NAFEMS

www.asme.org
www.nafems.org

A framework for verification and validation

ASME V&V 10 diagram

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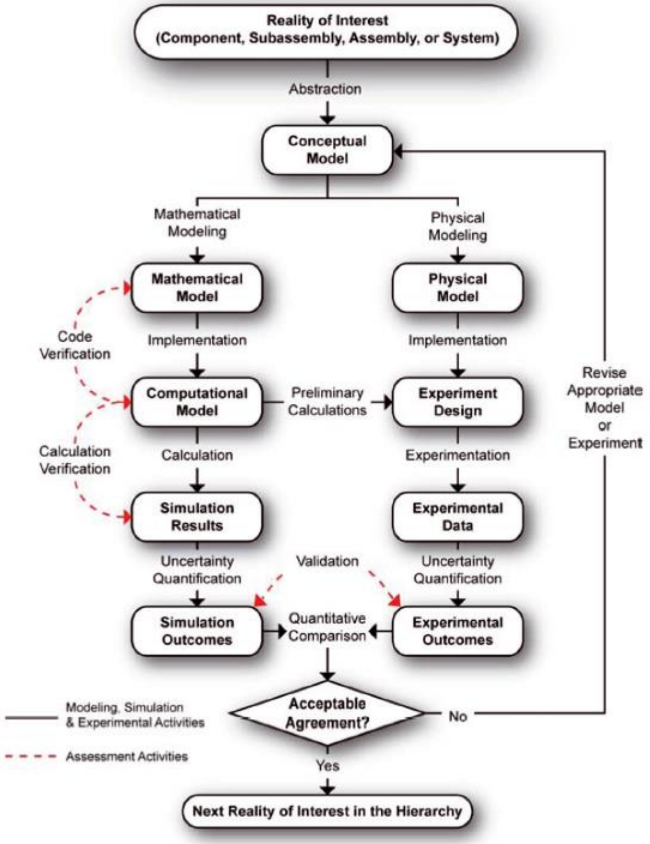
- Verification is:
  - the process of determining that a computational model accurately represents the underlying mathematical model and its solution.
- Validation is:
  - the process of determining the degree to which a model is an accurate representation of the real world from the perspective of the intended uses of the model.



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  - the … nal model acc … tical mo…

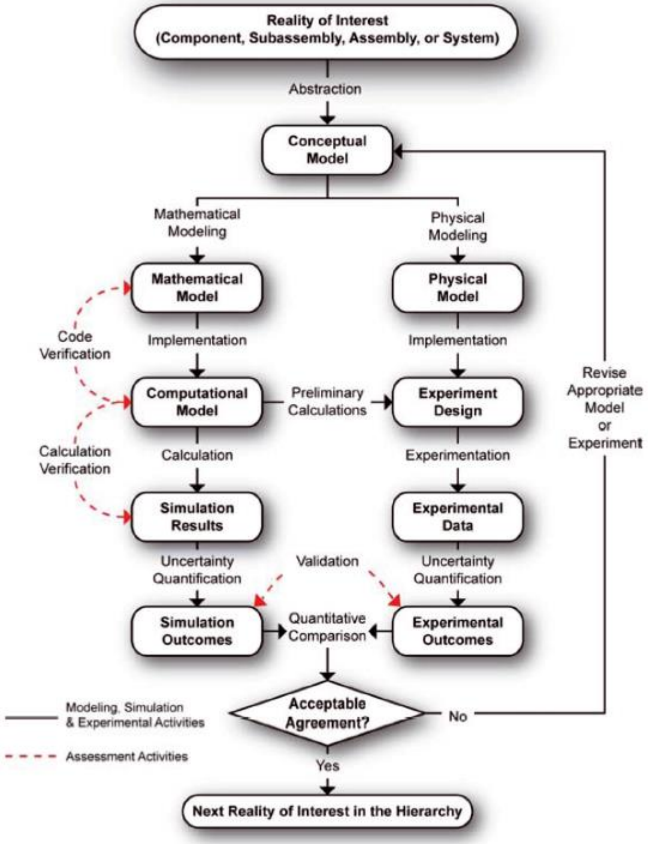
Mathematics

Are we solving the equations correctly?

- Validation is:
  - the … ch a model is a … d from the per…

Physics

Are we solving the correct equations?



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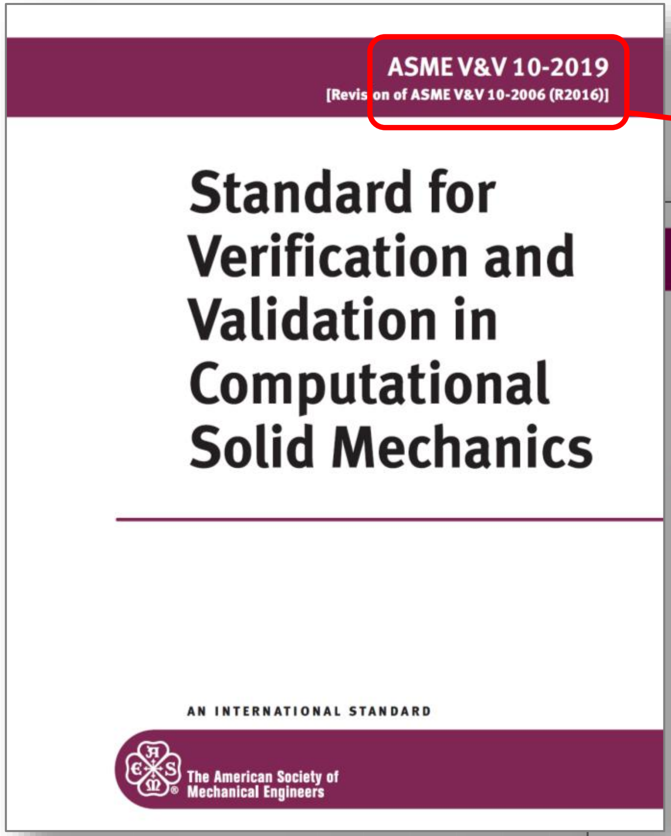


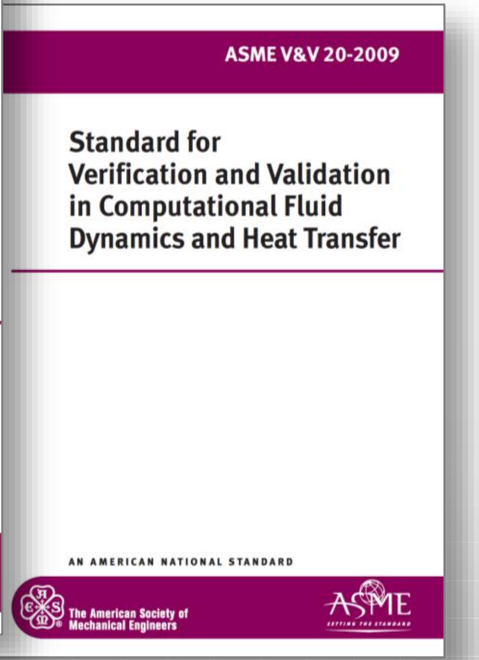
ASME V&V 10-2019
[Revision of ASME V&V 10-2006 (R2016)]

Standard for Verification and Validation in Computational Solid Mechanics

AN INTERNATIONAL STANDARD

The American Society of Mechanical Engineers

Updated in 2019



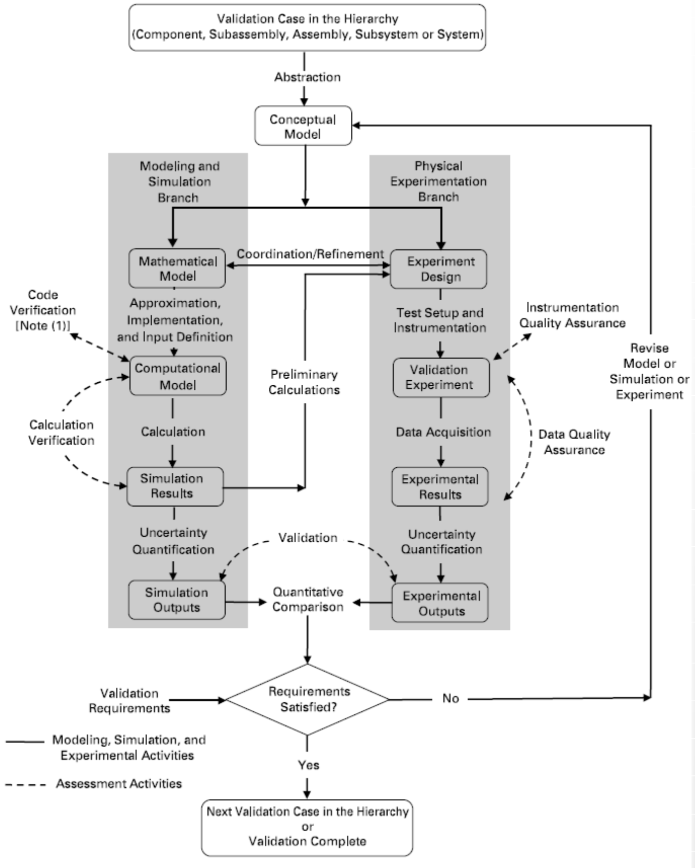
ASME V&V 20-2009

Standard for Verification and Validation in Computational Fluid Dynamics and Heat Transfer

AN AMERICAN NATIONAL STANDARD

The American Society of Mechanical Engineers

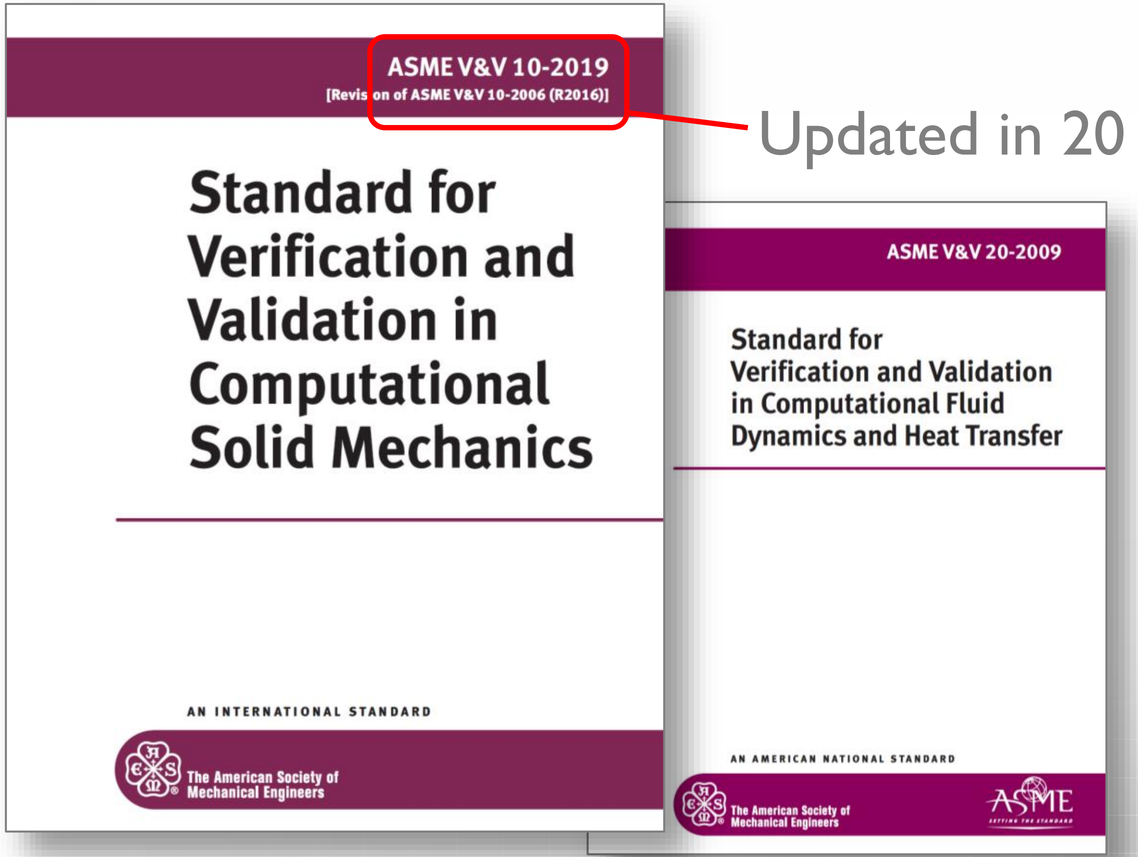
ASME V&V 10-2019



NOTE: (1) Code verification is performed using different models with closed-form or manufactured solutions.

A framework for verification and validation

ASME V&V 10 diagram



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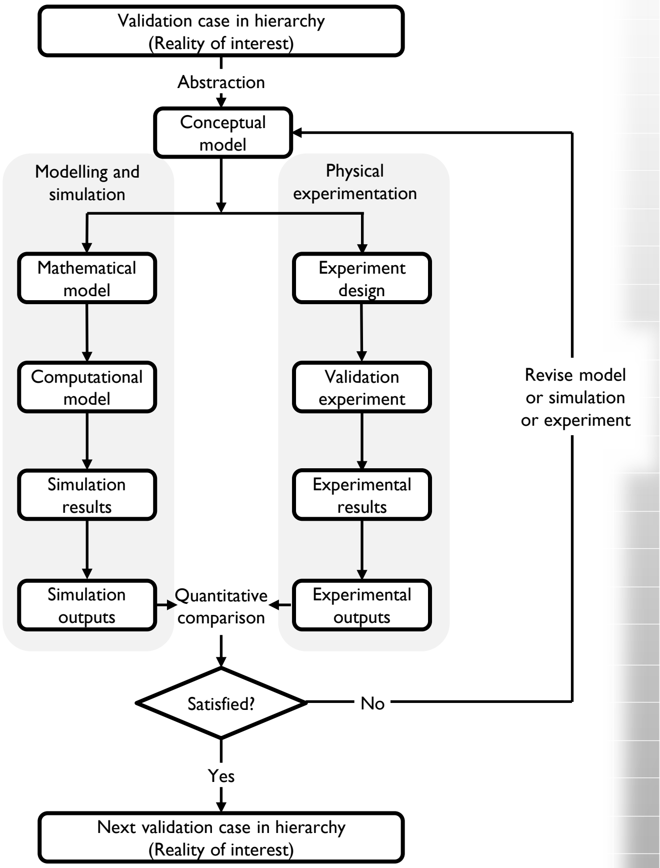


A framework for verification and validation

ASME V&V 10 diagram

- What is verification?

Code verification

Are the numerical algorithms correctly implemented in the computer code?
Are they functioning as intended?
Does the code correctly solve the underlying equations, as intended?

Calculation verification

Are the simulation errors sufficiently small?
(Round-off error, iterative error, discretization error, stochastic error.)

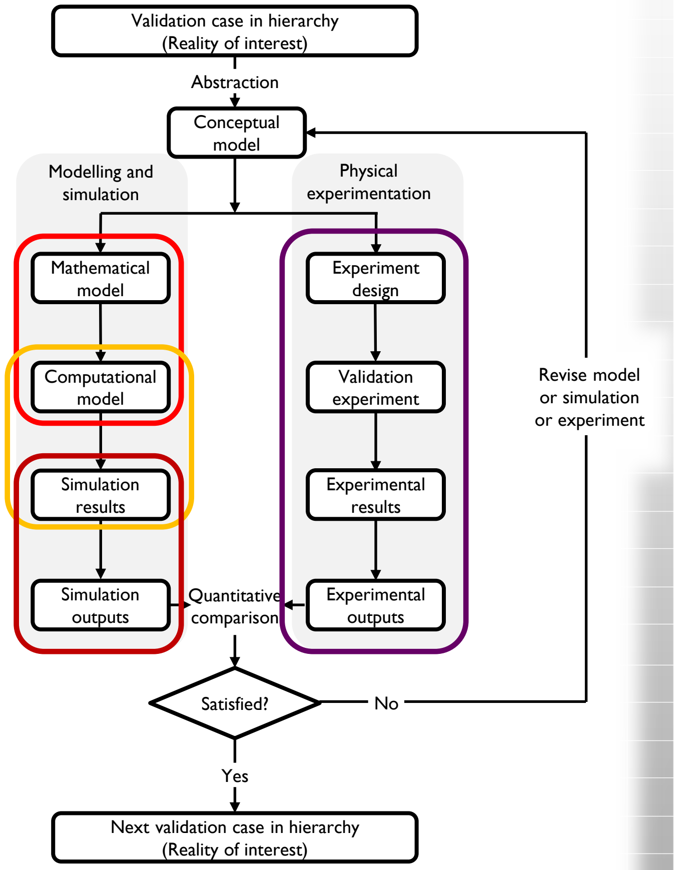
Uncertainty quantification

Are the simulation results sensitive to the simulation inputs?
UQ margins of uncertainty accumulate on top of any errors due to code and calculation verification.

Experimental branch

Similar quality assurance and UQ activities mirrored along the experimental branch.

(Derived from) ASME V&V 10-2019



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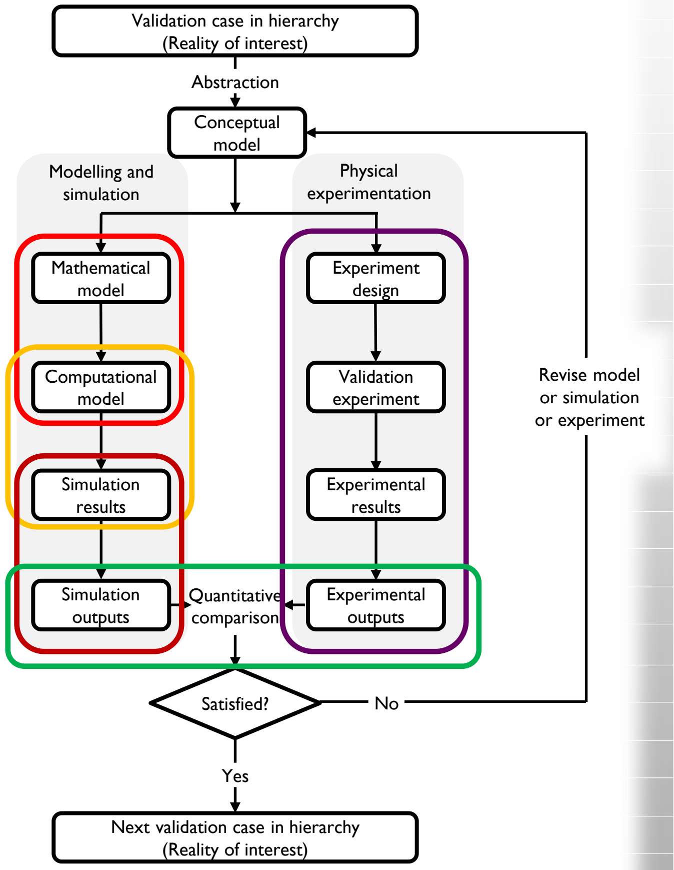
Validation

Quantitative comparison of simulation outputs with experimental outputs.
Is the prediction within the required bounds?
Not a comparison of single point data, but of predictive/experimental bounds.



(Derived from) ASME V&V 10-2019

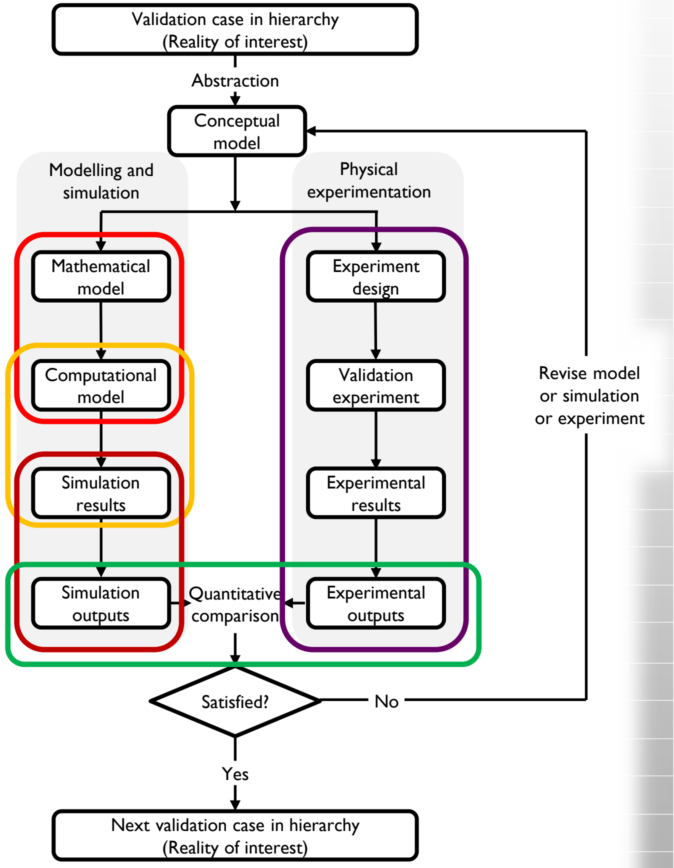
Validation case in hierarchy
(Reality of interest)
Abstraction
Conceptual model
Modelling and simulation
Physical experimentation
Mathematical model
Computational model
Simulation results
Simulation outputs
Experiment design
Validation experiment
Experimental results
Experimental outputs
Quantitative comparison
Satisfied?
No
Revise model or simulation or experiment
Yes
Next validation case in hierarchy
(Reality of interest)

A framework for verification and validation

ASME V&V 10 diagram

- What is validation?
  - From ASME V&V 10 2019:
    Validation is the process of determining the degree to which the model is an accurate representation of *corresponding physical experiments* from the perspective of the intended uses of the model.

(Derived from) ASME V&V 10-2019



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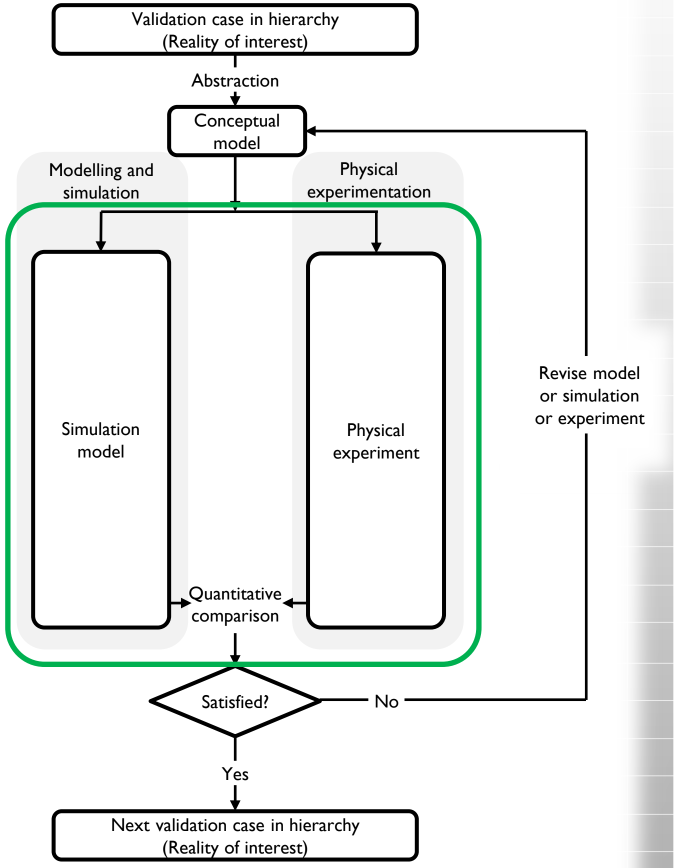

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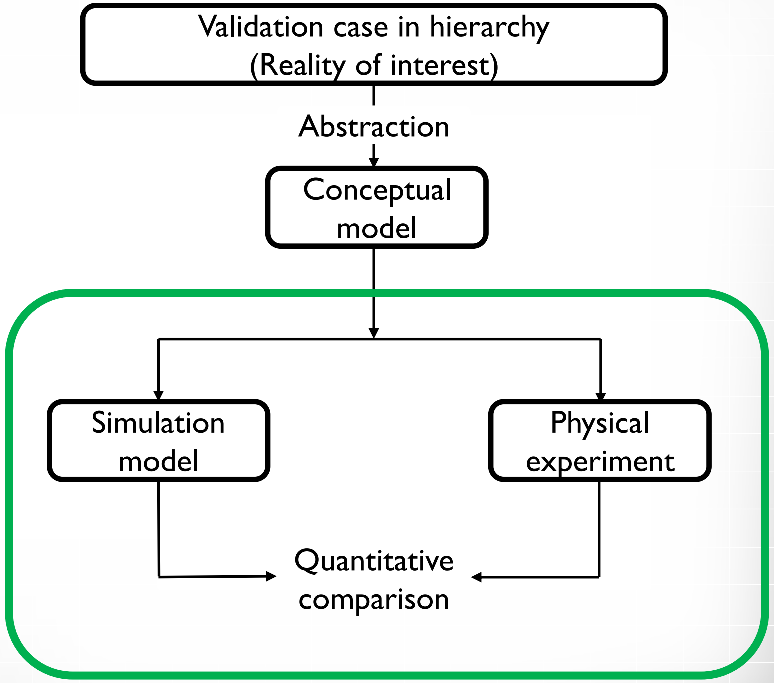

A framework for verification and validation

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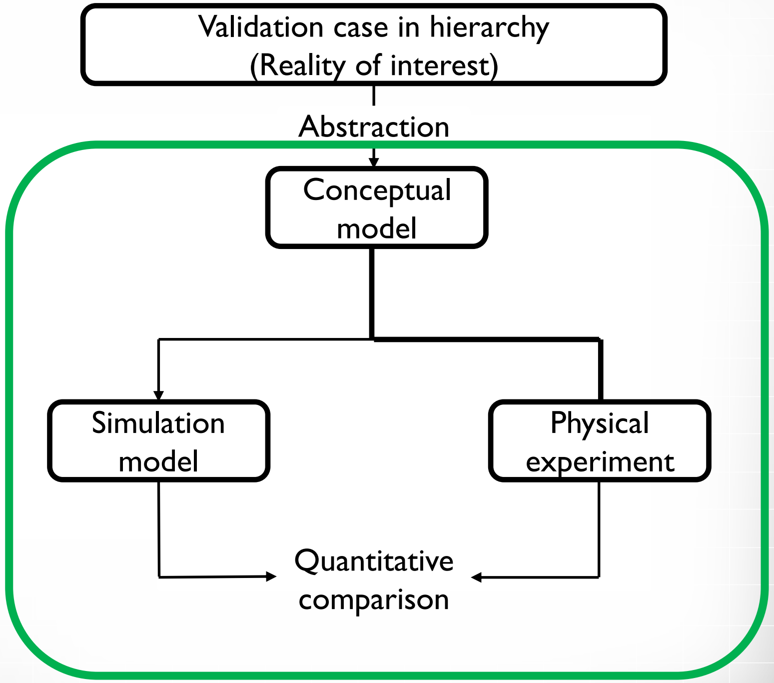

A framework for verification and validation

ASME V&V 10 diagram

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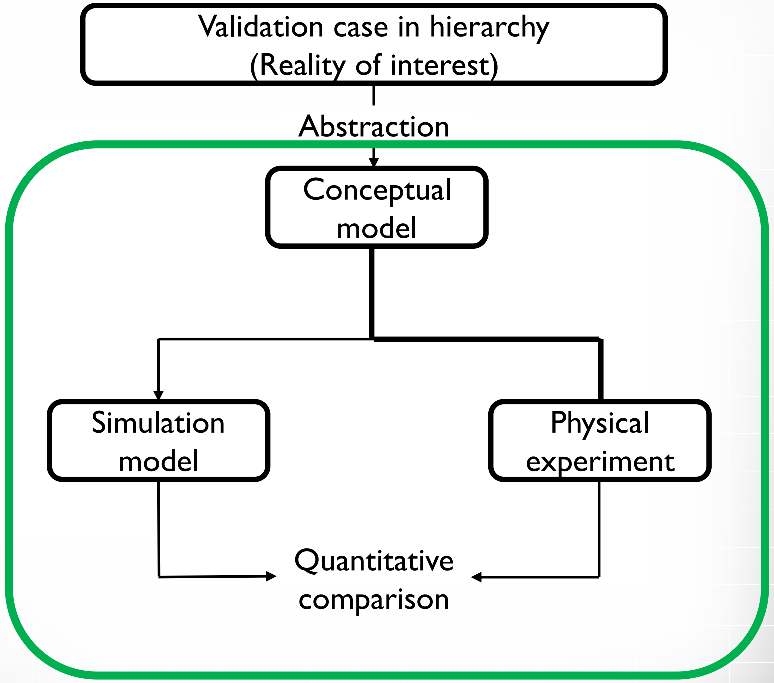
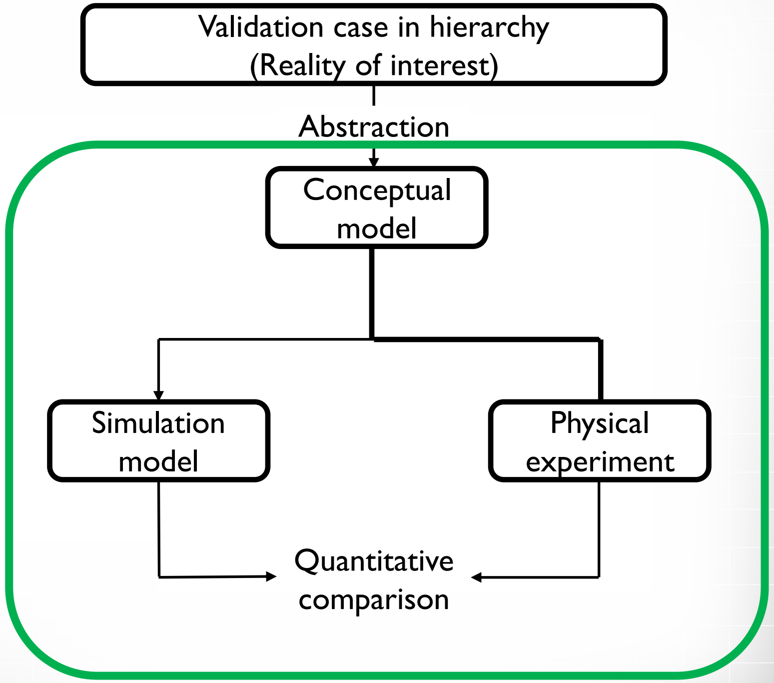


- What is validation?
  - From ASME V&V 10 2019: Validation is the process of determining the degree to which the model is an accurate representation of *corresponding physical experiments* from the perspective of the intended uses of the model.
  - The 2019 definition of validation is really focused upon the quality and management aspects of validation identified in the bottom part of the V&V 10 diagram. The quantitative comparison constituting the validation step in line with this definition is between the outputs of the simulation model and of corresponding physical experiments, **both of which derive from the conceptual model**.

Confidence and abstraction validation

ASME V&V 10 diagram

(Derived from) ASME V&V 10-2019



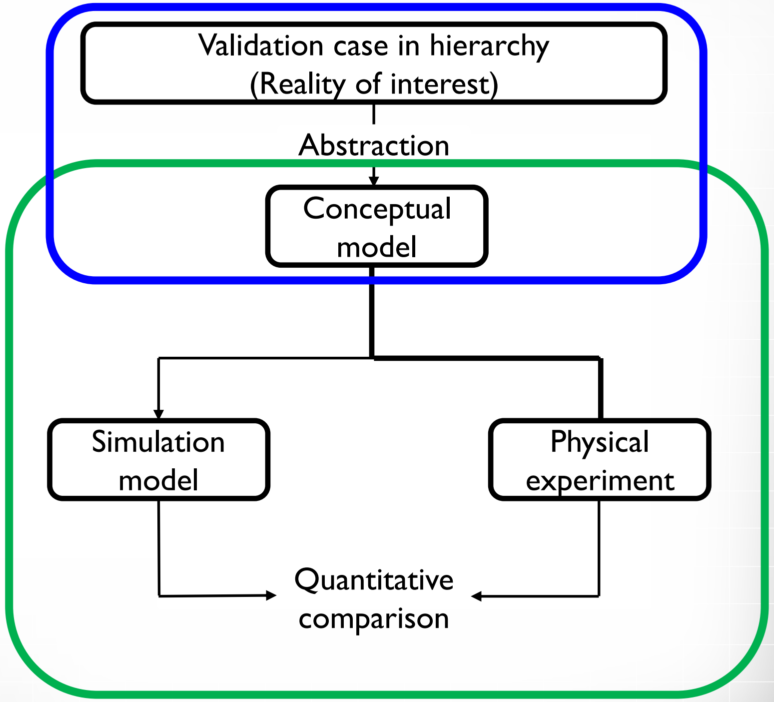
- What is validation?
  - From ASME V&V 10 2019: Validation is the process of determining the degree to which the model is an accurate representation of *corresponding physical experiments* from the perspective of the intended uses of the model.
- How can we be confident that our simulation predictions are an accurate representation of reality?
  - Are our experiments an accurate representation of our reality of interest?
  - Just like a computer simulation, a physical experiment is merely a simulation of our reality of interest, it is not the actual reality.

Confidence and abstraction validation

ASME V&V 10 diagram

(Derived from) ASME V&V 10-2019

- How can we be confident that our physical experiments are an accurate representation of our reality of interest?
  - If the abstraction process misses out some important physics, **the outcomes of the simulation and validation experiment might agree well with each other, but not necessarily with the reality of interest.**



Confidence and abstraction validation

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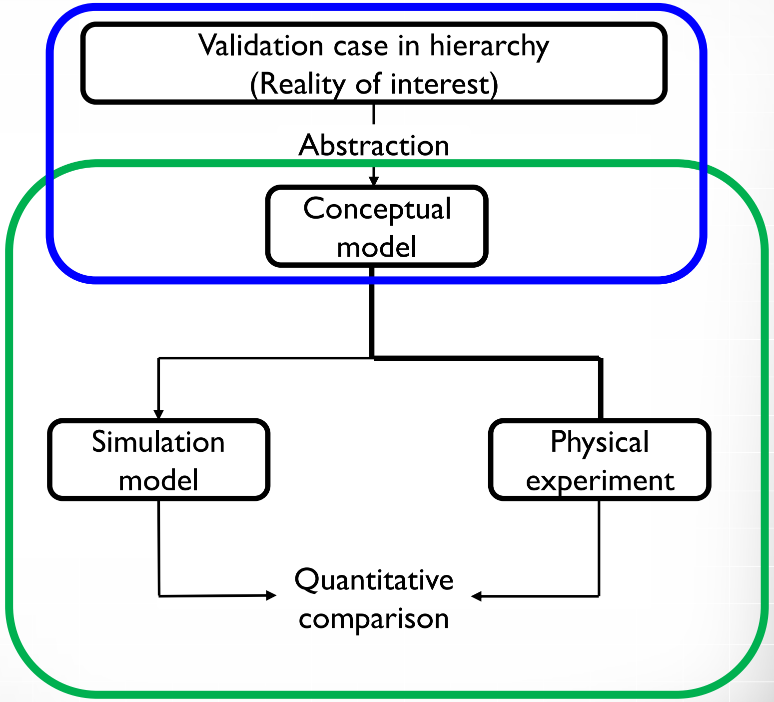


- Examples:
  - Bouncing F1 cars
  - Natural displacement ventilation of buildings*
  - Atmospheric dispersion within the built environment*
  - Fires in ship compartments*
  - Thermal cooldown/hydrate avoidance*.

* Discussed in detail in my NWC 2021 paper – please email me at steve.howell@abercus.com for a copy

Learnings from the bouncing F1 cars episode

- Prior to the on-track testing in Barcelona, the CFD simulation models and physical (wind tunnel) experiments may have agreed reasonably well with each other, but not necessarily with the reality of interest: on track at full scale.
- In previous years, the evolution of the cars has been more gradual and the simulation models have (presumably) been adequate for pre-testing development.
- In 2022, the re-introduction of ground effect has introduced additional physics that had for years been safely neglected from the conceptual model for flat-bottomed cars, specifically the fluid structure interaction relating to the porpoising mechanism discussed earlier – this aspect of the physics is clearly relevant for the class of 2022, but was seemingly widely missed from the conceptual model during pre-testing development.

Learnings from the bouncing F1 cars episode

- With respect to the wind tunnel modelling undertaken before pre-season testing, the precise reason for this remains unclear – it is simply not possible to accurately represent all aspects of the physics relevant at full-scale within a scale model physical experiment.
  - Stiffness of the car: a scale model may be relatively stiffer than a full scale car, and the flow velocities in the wind tunnel will be lower than those on the track. In combination, it is possible that any physical distortion to the shape of a model car in the wind tunnel due to tyre squash or distortion of the body panels under aerodynamic loading could be less significant than that of a full scale car running on track at the equivalent condition.
  - Stiffness of the apparatus: the rolling road apparatus used in the wind tunnel is flexible and may deform, particularly when the clearance between the car and the rolling road is small. This may unintentionally relieve the porpoising effect by allowing the gap between the underside of the car and the road surface to be relatively larger in the wind tunnel than on track.

Learnings from the bouncing F1 cars episode

- It may have been that the wind tunnel and CFD gave some early indications of the porpoising issue, but that the specific tests highlighting this effect may have not been properly understood and could have been dismissed as invalid or as outliers.
- To reiterate, I am an outsider to Formula 1, but I hope that in due course the F1 teams will be able to share what happened more clearly with NAFEMS so that the simulation community can collectively learn from this.
- However, it does not necessarily matter precisely what the shortcomings of the wind tunnel may have been; it will suffice to recognise that there must have been differences in the physics relevant to porpoising between the wind tunnel and the full scale on track testing, and that these differences were not identified until the pre-season testing on-track in Barcelona in February.

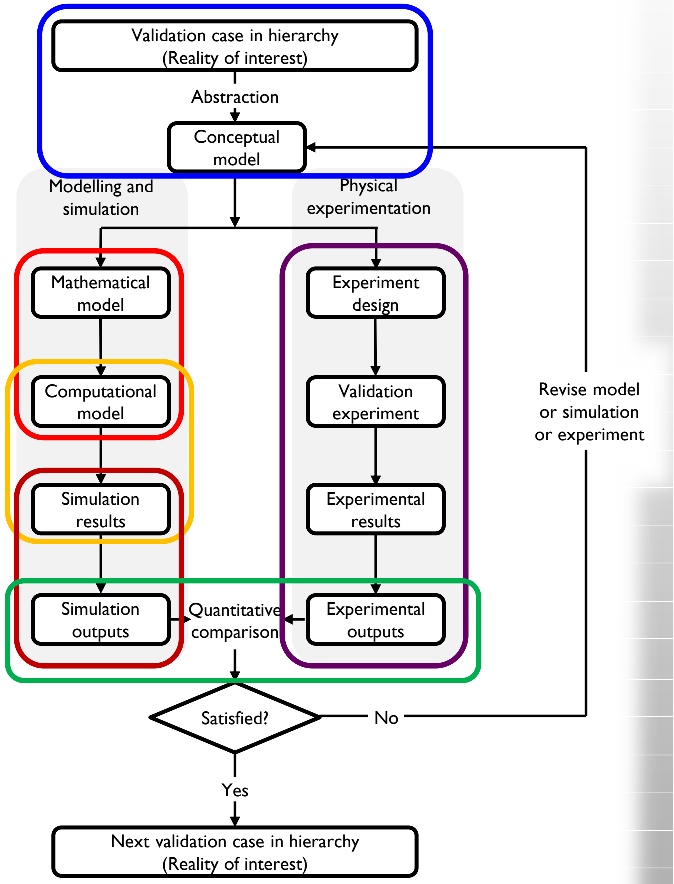
What this means for the wider use of simulation

- The bouncing cars episode does not represent a failure of the simulation tools, or of the simulation process. In fact, it represents a success because porpoising was identified before the start of the first race.
- What has clearly been demonstrated is the benefit of having full-scale testing as part of the development process – even though today's simulation tools are now mature tools with decades of investment and development that can provide levels of understanding that was not previously possible, this does not mean that they should be used as *out-of-the-box* solutions.
  - This may not be news to the audience here today, but it is useful to have a high-profile case study that can serve as a reminder to the wider engineering community.

What this means for the wider use of simulation

- The limiting factor in having confidence in the simulation predictions does not necessarily relate to the simulation tools themselves, but more to how they are used and applied in practice.
- Reverting to the V&V 10 diagram, the software tool itself is only a small part of the diagram (code verification), but to have confidence in simulation predictions requires the diagram to be considered in its entirety.
- This is the responsibility of the simulation user rather than the code developer, and represents a significant investment of effort that must not be underestimated.

(Derived from) ASME V&V 10-2019



Improving confidence through blind benchmarking

- Perhaps the best way to gain confidence in engineering simulation is through blind benchmarking – this is a true test of the simulation process.
- The pre-season testing in Barcelona essentially became a very public blind benchmarking opportunity – even in F1, there is still a risk that simulation predictions may not capture important physics for the reality of interest.
- It is as important as ever to undertake blind benchmarking to challenge our understanding of how reliable the process of engineering simulation really is.
- As an industry, we need to be careful not to believe our own rhetoric, and ensure that our expectations of engineering simulation are supported more widely by blind benchmarking and other validation activities.

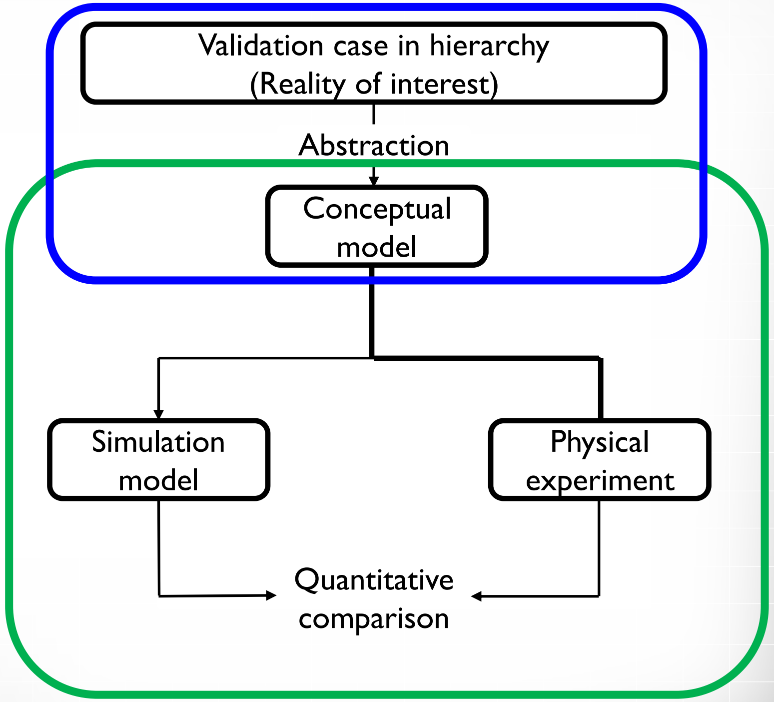
Improving confidence through blind benchmarking

- In my experience, most blind benchmarking exercises show that there can be significant variation in simulation predictions when the process is blind, even if participants are using the same simulation code.
  - Of course, these variations can be reduced once the comparison data has been released and participants have the chance to modify their simulation model to improve agreement, but this in itself demonstrates the value of blind benchmarking.
- As an industry, it is important to recognize and acknowledge such variations, because then we're in a much better position collectively to address it.
- Maybe, in future, there could be regular blind benchmarking challenges organized by IMechE and/or NAFEMS?

The practicalities of the abstraction process

- The bottom part of the V&V 10 diagram relating to validation quality is detailed in ASME V&V 10.
- For the top part of the diagram, however, the practicalities of the abstraction process are less well defined.
- The latest contribution from NAFEMS is to recommend that a PIRT analysis be undertaken to formally identify the important physical phenomena for any particular validation case (Imbert et. al. , NAFEMS VVUQ 2021).

(Derived from) ASME V&V 10-2019

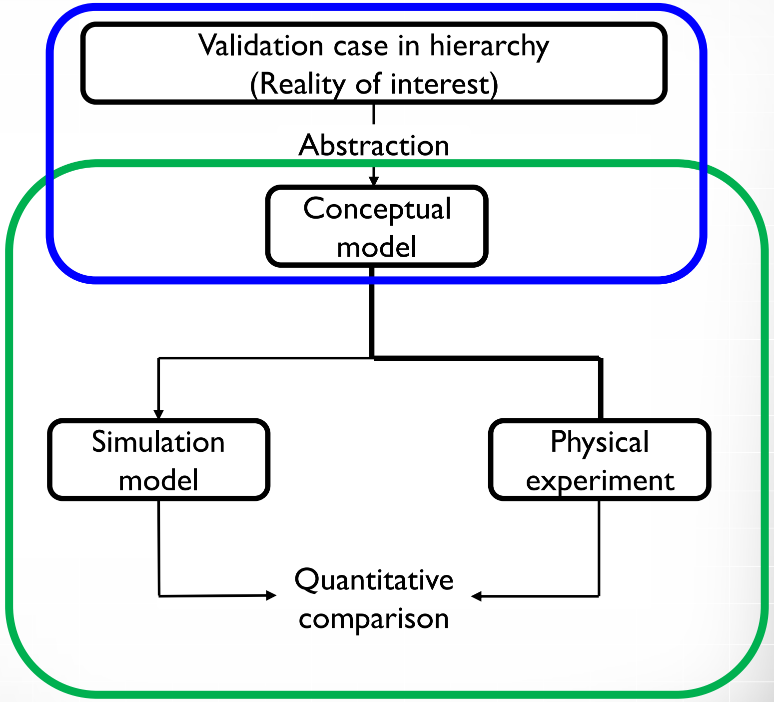


* Phenomena Identification and Ranking Technique

The practicalities of the abstraction process

- By its very nature, a PIRT analysis is somewhat subjective: what is considered to be an important phenomenon by one expert may be viewed differently by another.
- To improve the rigour of this process, it could be useful to create a database of PIRT analyses for common types of simulation analysis, so that knowledge is shared and consensus is arrived at from as wide a pool of subject matter experts as possible – perhaps there could be a role here for IMechE and/or NAFEMS in future?

(Derived from) ASME V&V 10-2019

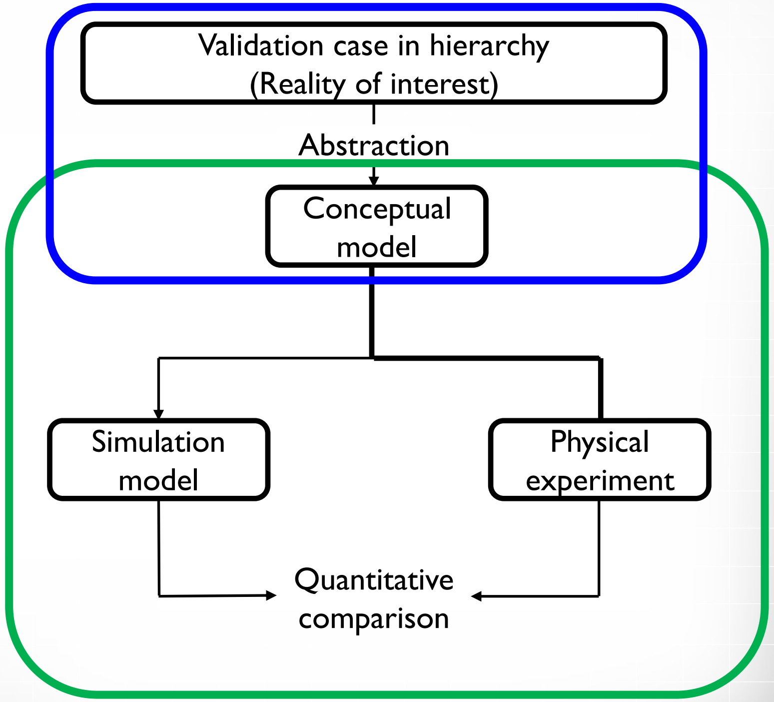


* Phenomena Identification and Ranking Technique

The practicalities of the abstraction process

- Can we devise some simple processes to illustrate the rigour of the validation activities, both validation quality and abstraction validation, so that they can be better understood?

(Derived from) ASME V&V 10-2019



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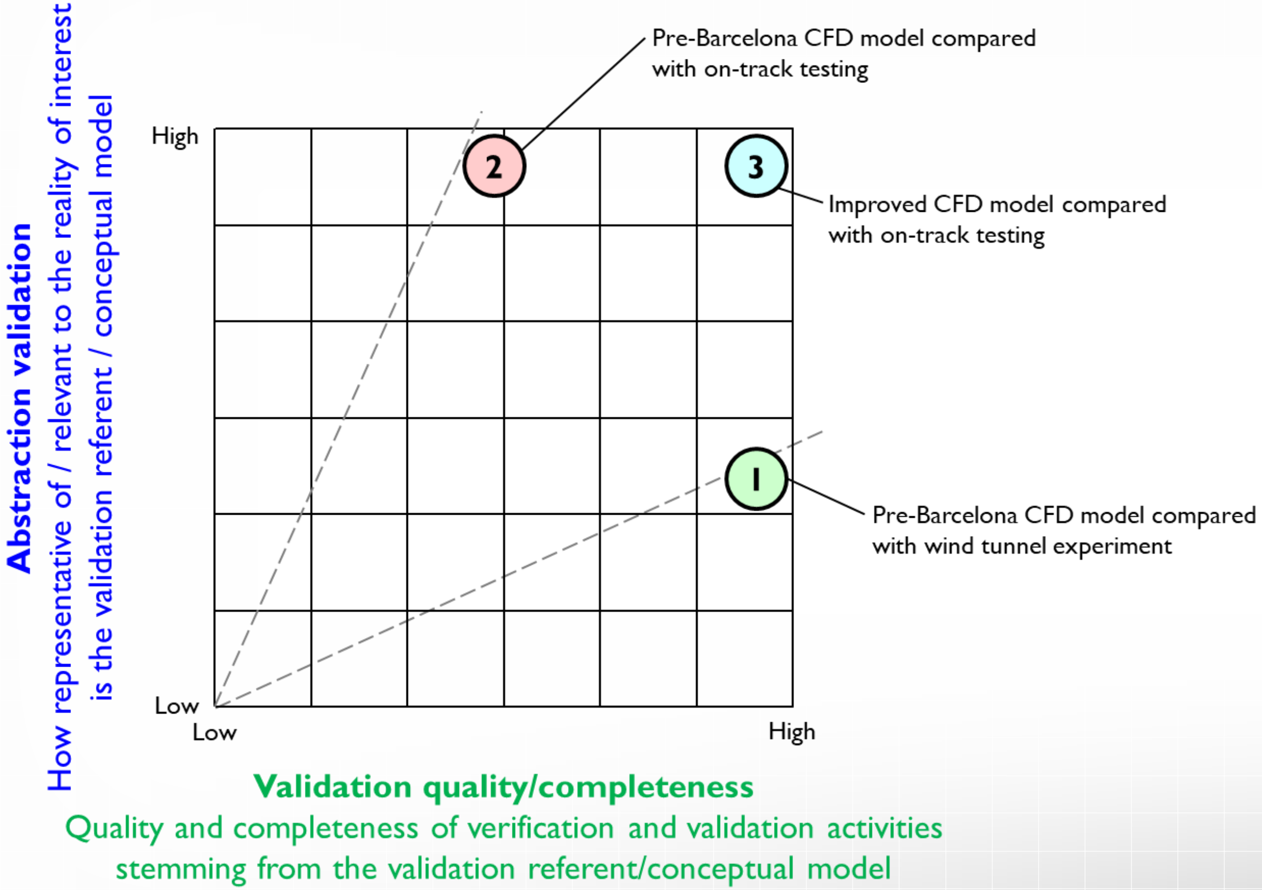

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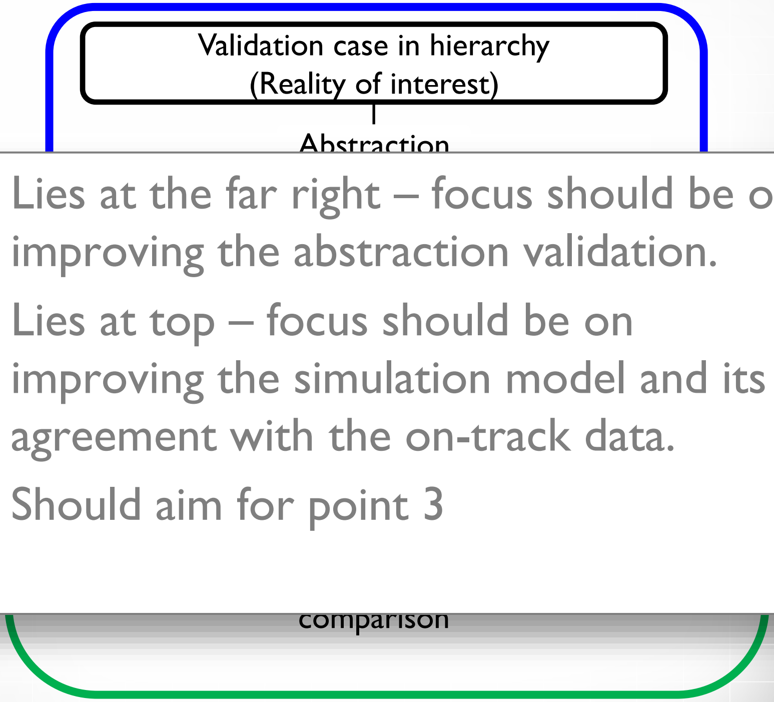
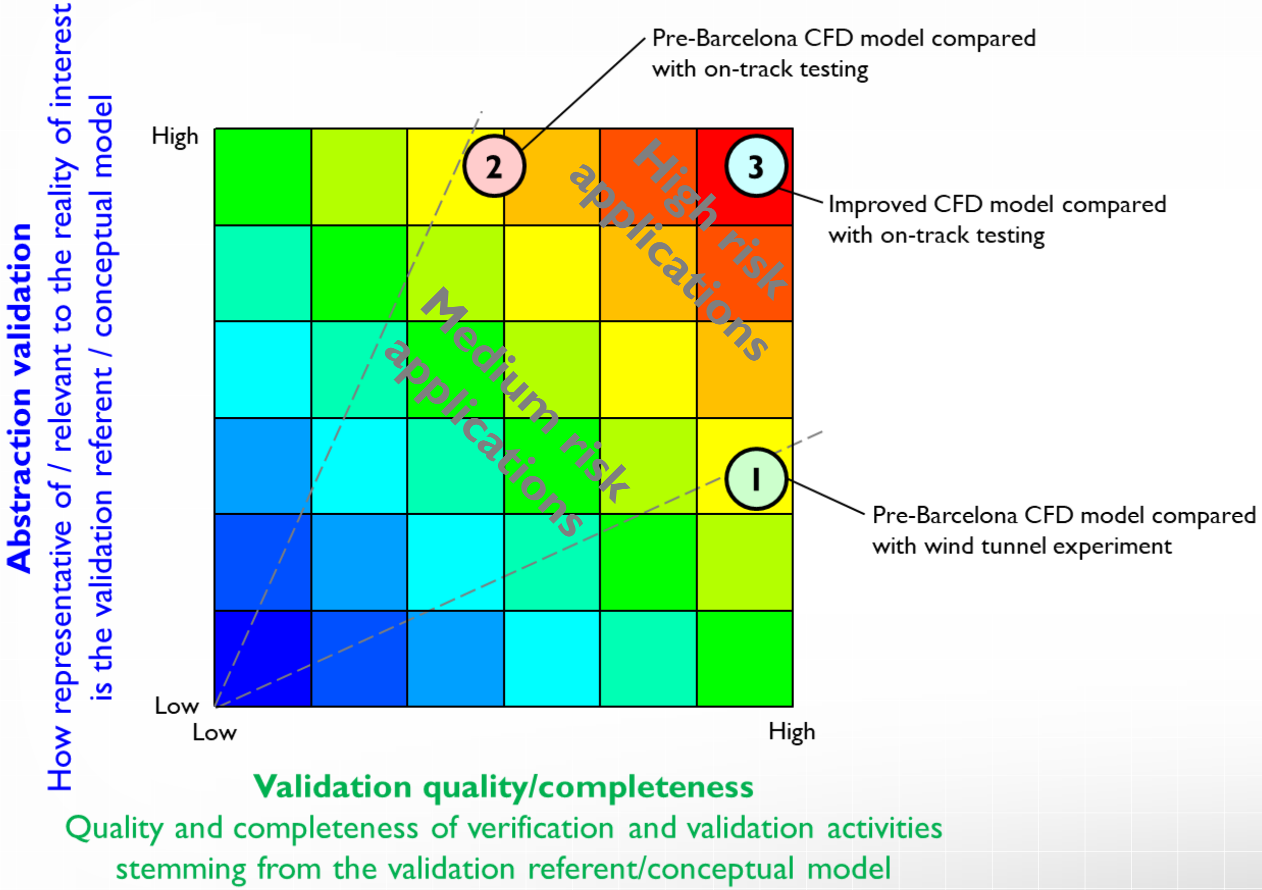


1. Lies at the far right – focus should be on improving the abstraction validation.
2. Lies at top – focus should be on improving the simulation model and its agreement with the on-track data.
3. Should aim for point 3

The practicalities of the abstraction process



Pre-Barcelona CFD model compared with on-track testing

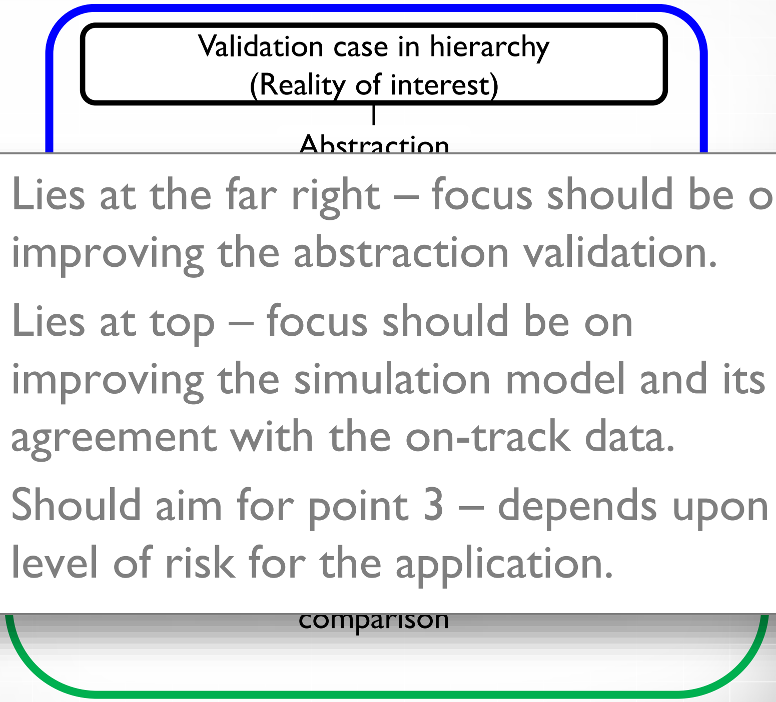
Improved CFD model compared with on-track testing

Pre-Barcelona CFD model compared with wind tunnel experiment

Abstraction validation
How representative of / relevant to the reality of interest is the validation referent / conceptual model

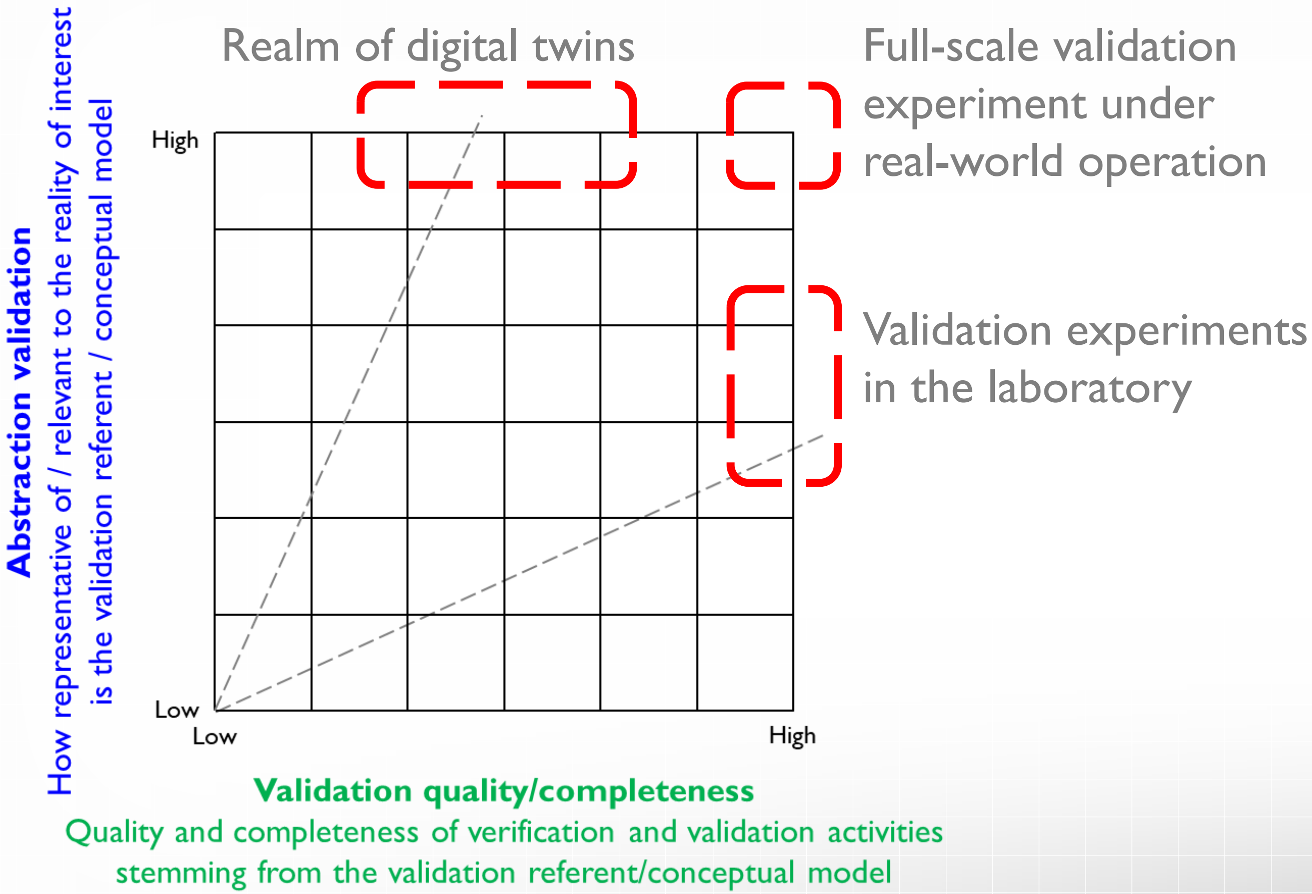
Validation quality/completeness
Quality and completeness of verification and validation activities stemming from the validation referent/conceptual model

(Derived from) ASME V&V 10-2019



1. Lies at the far right – focus should be on improving the abstraction validation.
2. Lies at top – focus should be on improving the simulation model and its agreement with the on-track data.
3. Should aim for point 3 – depends upon level of risk for the application.

The practicalities of the abstraction process



Realm of digital twins

Full-scale validation experiment under real-world operation

Validation experiments in the laboratory

Abstraction validation
How representative of / relevant to the reality of interest is the validation referent / conceptual model

Validation quality/completeness
Quality and completeness of verification and validation activities stemming from the validation referent/conceptual model

In conclusion

- If there are important physics missing from the physical experiment, **the outcomes of a simulation model and physical validation experiment can agree very well with each other, but not necessarily with the reality of interest**.
- The benefit of having full-scale testing as part of the development process has clearly been demonstrated. **Simulation tools should not be used as *out-of-the-box* solutions.**
  - To have confidence in simulation predictions requires the V&V 10 diagram to be considered in its entirety – this is the responsibility of the user of the simulation code, not the code developer, and represents a significant investment of effort.
- **A digital twin is only good enough as the validation activities that underpin it.**

In conclusion – opportunities for IMechE/NAFEMS

- The practicalities of the abstraction process remain abstract and further guidance is needed. The latest contribution from NAFEMS recommends that a PIRT analysis be undertaken – this subjective since it depends upon expert opinion and peer review.
  - **Opportunity for IMechE/NAFEMS** – create a database of PIRT analyses for common types of simulation analysis, so that knowledge can be shared and consensus can be arrived at from as wide a pool of subject matter experts as possible.
- It remains as important as ever to have blind benchmarking events to challenge our understanding of how reliable the process of engineering simulation really is.
  - **Opportunity for IMechE/NAFEMS** – organize regular independent blind benchmarking challenges, to continually challenge our understanding of how reliable the process of engineering simulation really is. As an industry, it is important to recognize and acknowledge issues, because then we're in a much better position collectively to do something about it and improve.

Contact us

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