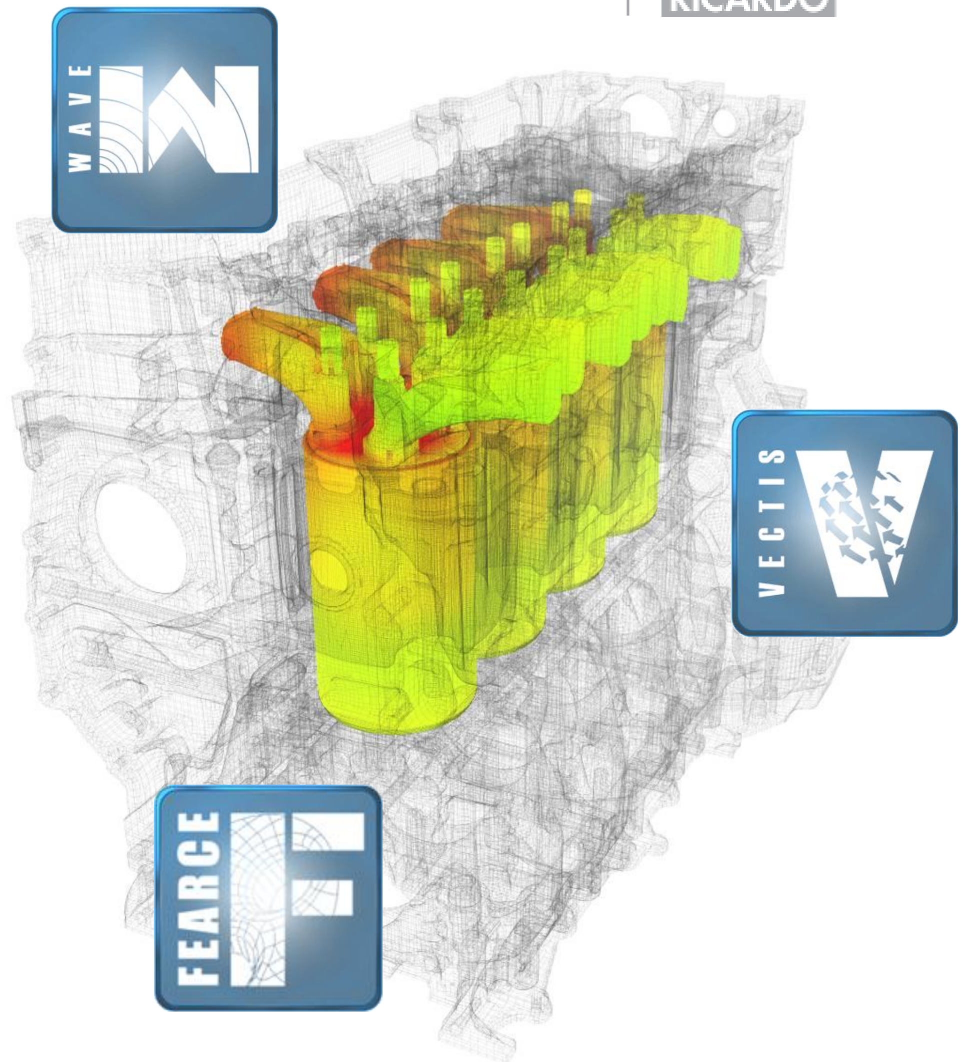
Engine Thermal Analysis

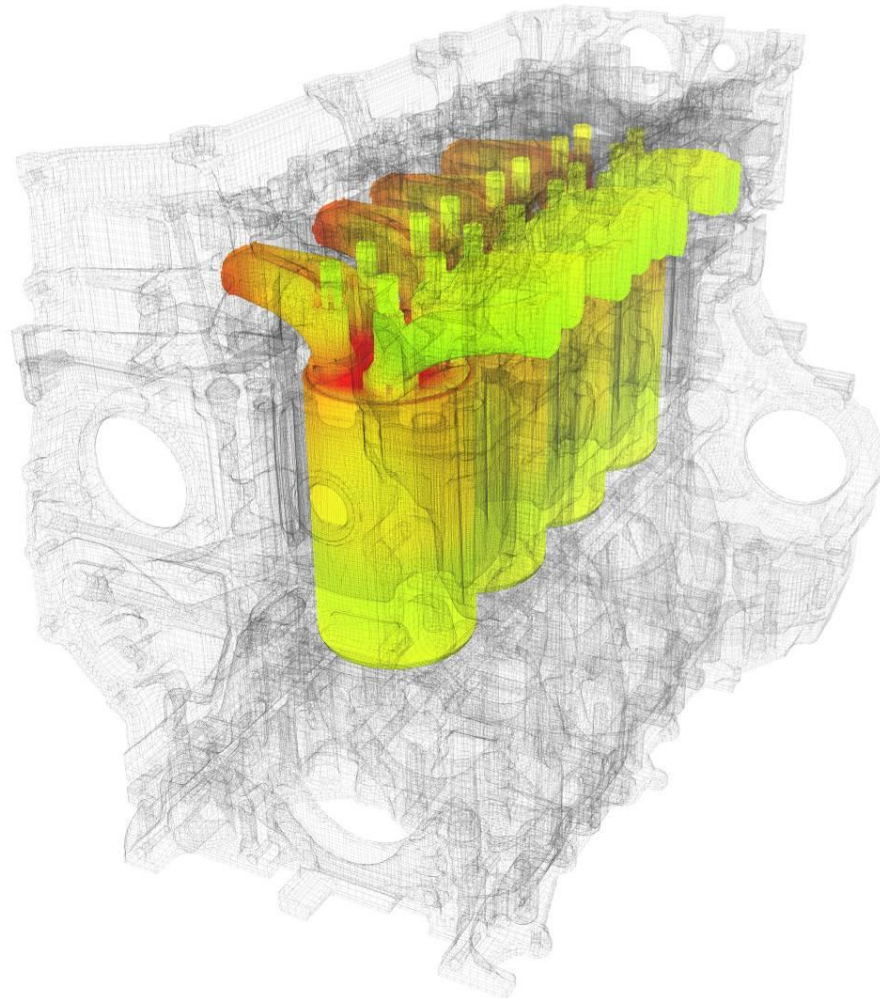
The Thermal Problem
(a hot topic!)

January 2013



The Thermal Problem

- **A Background To The Need**
- **Analysis Options**
- **We're All In It Together**
- **The Ricardo Solution**



A BACKGROUND TO THE NEED

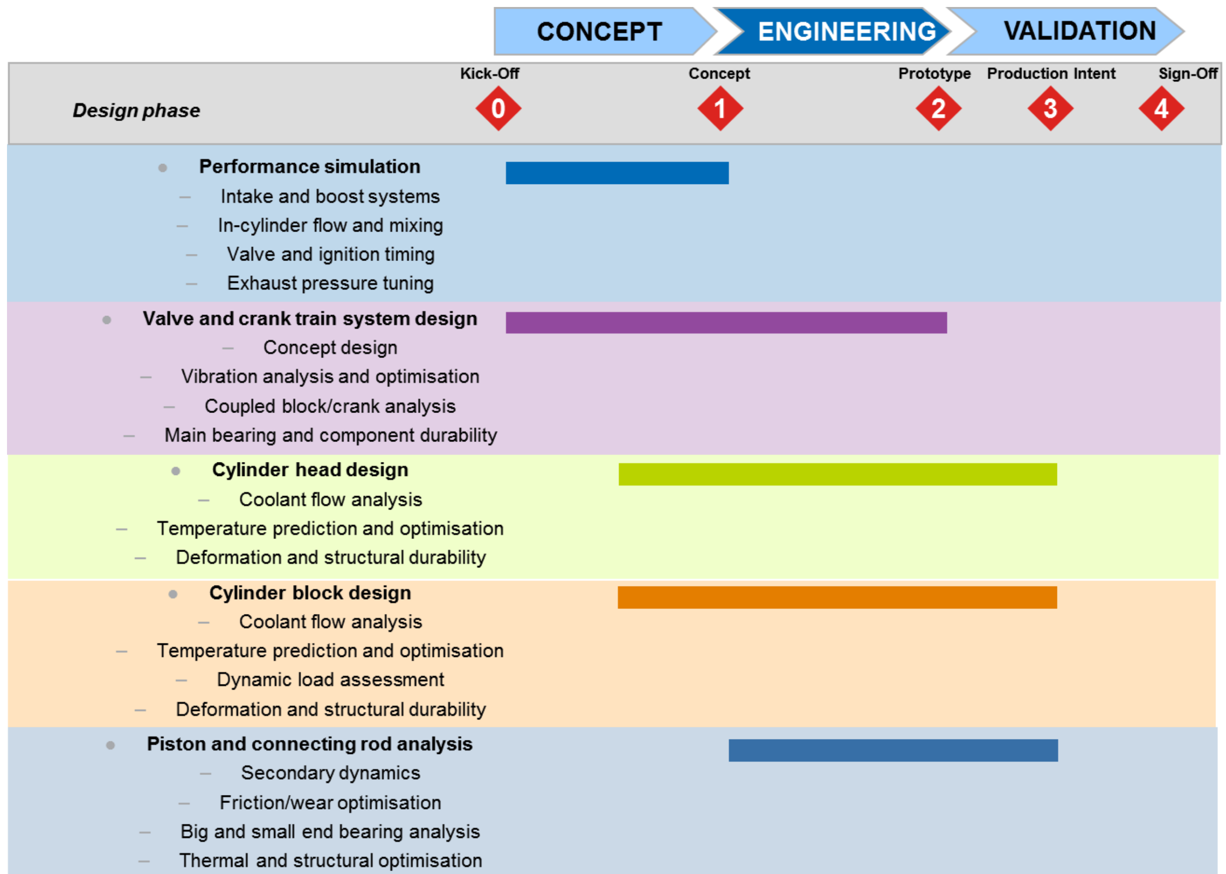
A background to the need

- There is no escaping the fact that the internal combustion engine gets hot
  - …and to temperature levels that have a significant effect upon both the performance of the system and its structural integrity
- As such accurate information for the temperature distribution throughout a powertrain structure is vital for the successful analysis of many key aspects in engine design, including;
  - Management of the actual thermal warm-up from cold to optimum conditions
    - Vital for combustion performance and emissions control
  - Structural integrity of the main powertrain
    - Especially the cylinder head, block and exhaust manifolds
  - Piston performance and durability
    - Controlling clearances of the piston and ring system to minimise friction, noise and lubrication loss amongst other things

A background to the need

- Many of these aspects have to be controlled very early in the design cycle of the powertrain
  - …and in fact would ideally be considered as early as the concept phase

- As such, having an accurate knowledge of the thermal distribution in the engine structure is key to allowing analysis to lead the design process
  - and so reduce expensive and time consuming prototype and testing activities



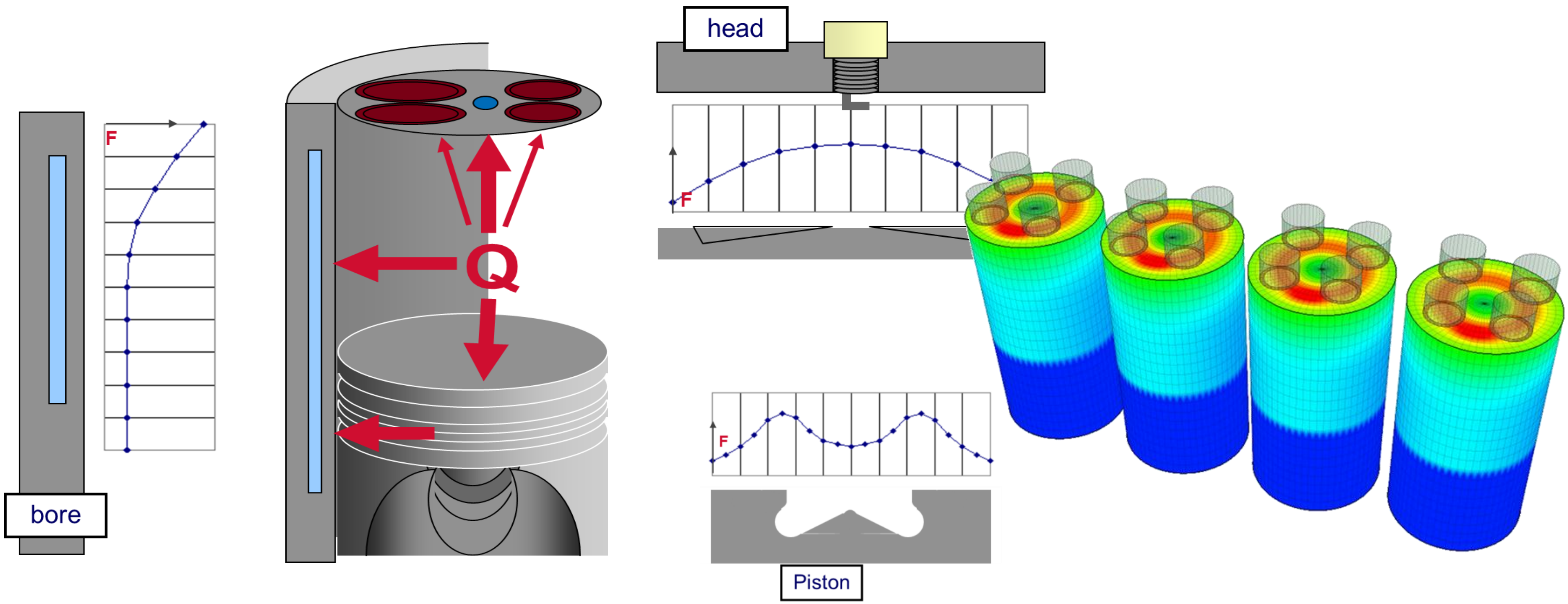
A background to the need

- Obviously as we are trying to provide design guidance before testing, we cannot rely on testing itself to produce the thermal measurements required
  - So we are going to have to use predictive methods to successfully capture thermal effects early in the design phase
- Any attempt to derive the temperature distribution analytically relies heavily on the accuracy of the boundary conditions used
  - The key difficulty for obtaining boundary conditions comes from predicting the heat flux as a result of the combustion which acts on the cylinder liner, the flame face, the intake and exhaust valves and ports and the piston assembly
- There are generally three analytical methods available to predict the heat flux from combustion
  - The use of empirical equations and databases
  - 1D gas dynamic simulation
  - Full in-cylinder CFD combustion analysis
- Each of these presents their own engineering challenges as we shall see from the next slides

ANALYSIS OPTIONS

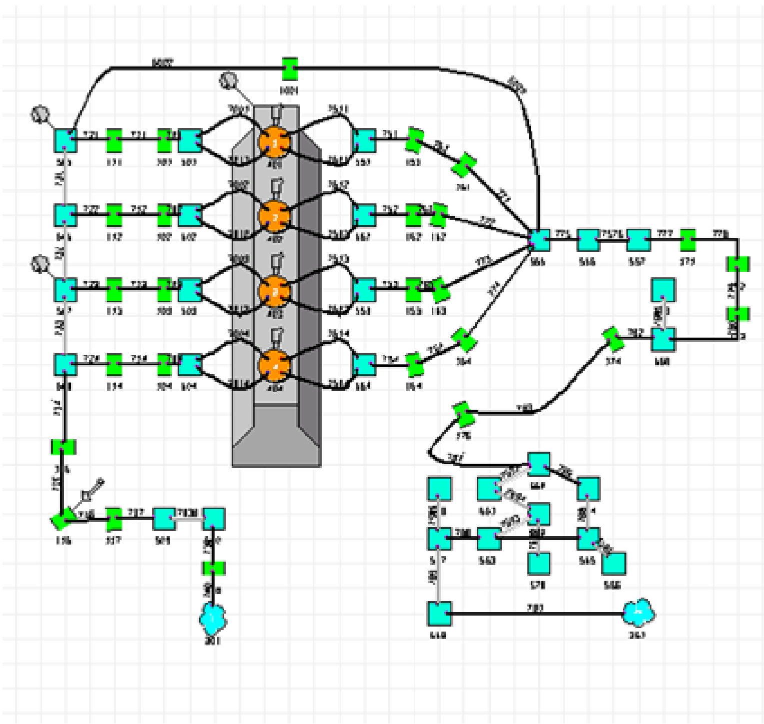
Current systems and their limitations
Empirical methods

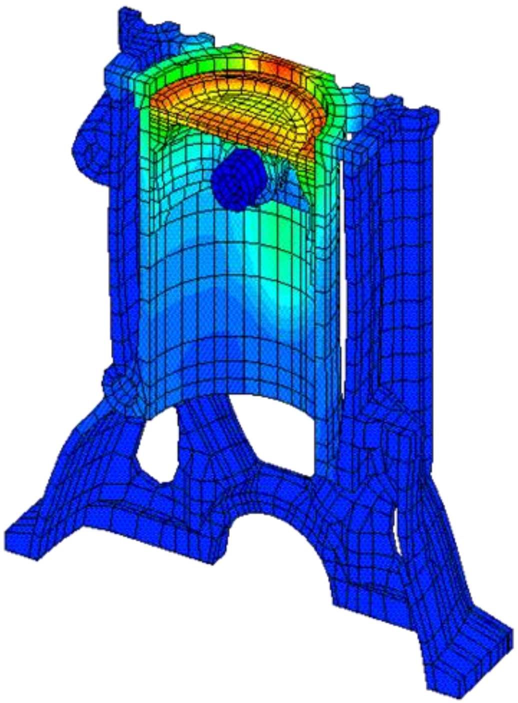
- The use of empirical equations and databases
  - This is a very fast method and can yield accurate results, but relies heavily on past experience of engines of a similar family
    - The method is effectively using test bed data from previous experience to make predictions for the next generation of engines
    - As such the method is not open to newer companies or novel engine design



Current systems and their limitations
1D analysis

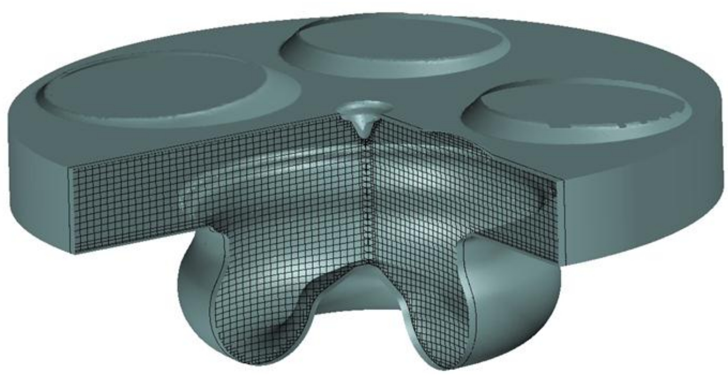
- 1D gas dynamic simulation
  - This is also a fast method and only requires parameters associated with the current design
    - However, although the calculation of total heat flux in the cylinder can be very accurate, there is poor spatial resolution and so the method does not provide a distribution good enough for accurate thermal analysis

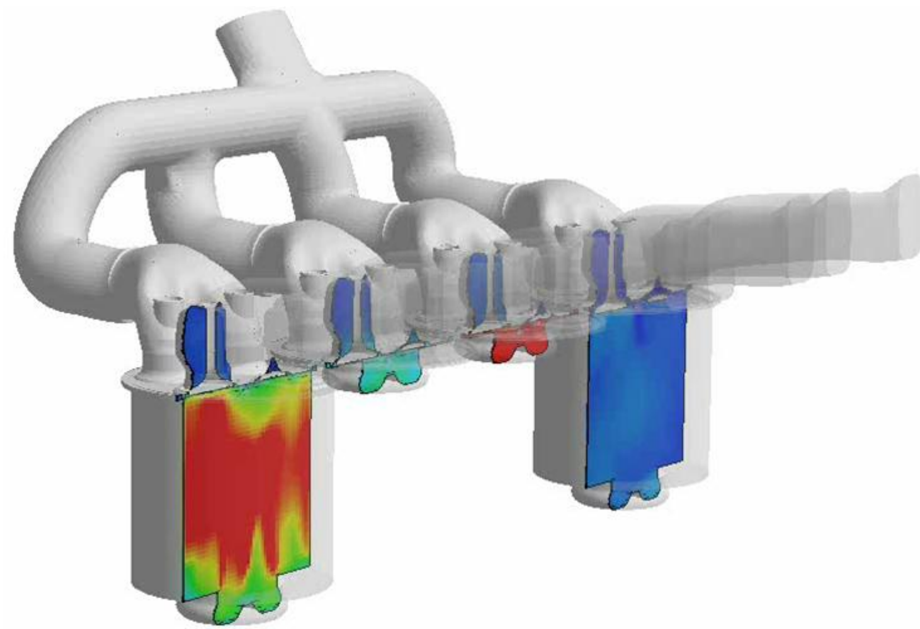




Current systems and their limitations
Full in-cylinder analysis

- Full in-cylinder CFD combustion analysis
  - This is the only accurate fully analytical method that provides a discrete enough spatial resolution for useful thermal prediction
    - The downside is that it is a complex study requiring a good understanding of spray and combustion modelling
    - The analysis can also be time consuming
      - Traditionally the time taken for this analysis has meant it is used in research rather than general engineering development





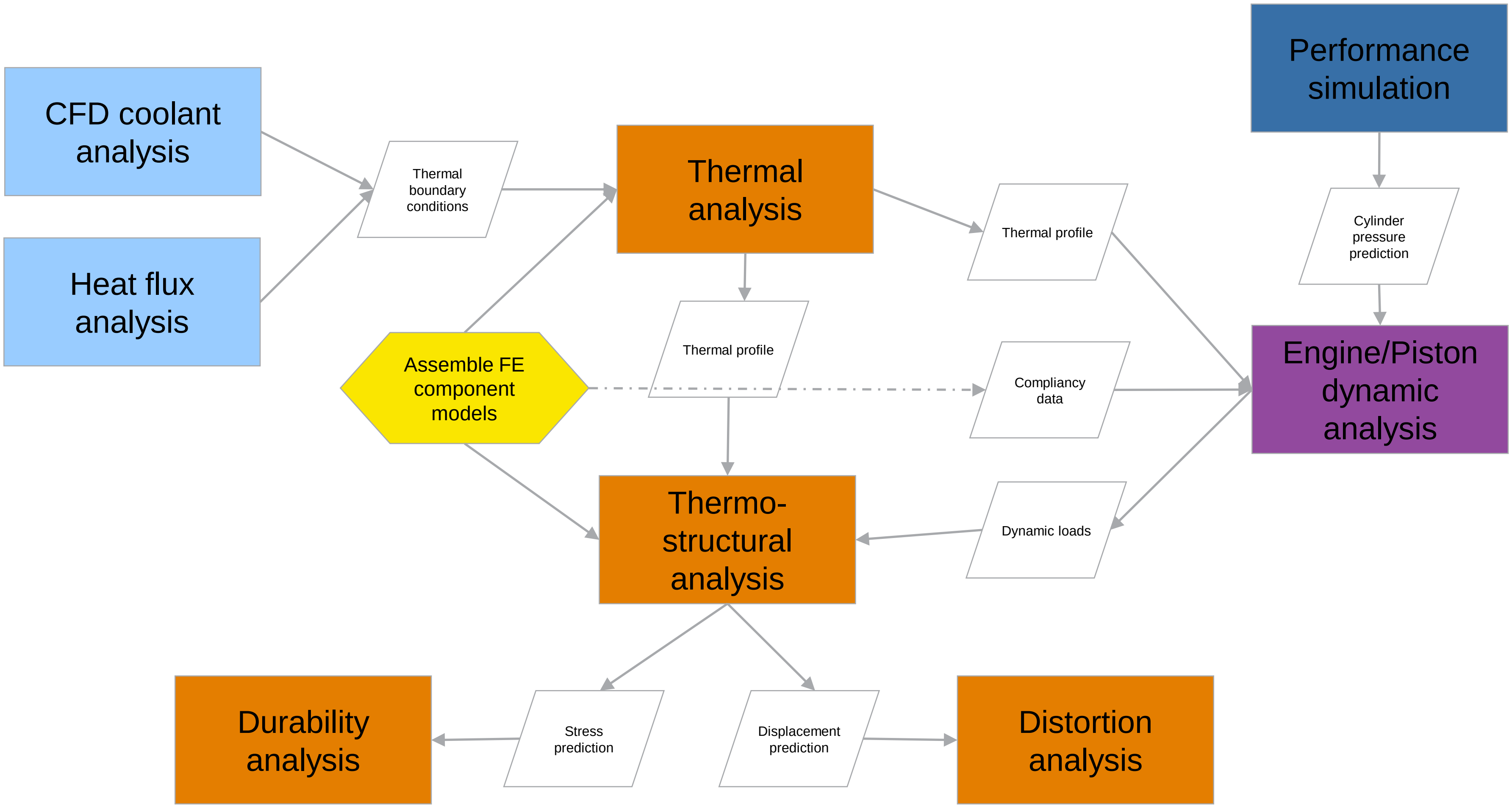
Today's issue and tomorrow's problem

- As the thermal prediction is critical to so much of the engine design, there is pressure to ensure that the temperature distribution is delivered as early as possibly in the project
  - These time constraints mean that the faster predictive methods are usually employed
    - Certainly for any concept work or in batch 1 engine development
  - Hence a lot of analysis today is based upon 1D prediction with tuning from either empirical data or test bed measurements
    - Consequently results are either low in accuracy or time delays are incurred awaiting test bed measurements before comprehensive structural studies can be completed
- Further, new legislation on emissions and constant pressure to improve economy also means that new engine developments are often using novel air handling, spray and combustion systems
  - This means that there is now little or no comparable data from similar designs that can be used in empirical predictions or tuning
- As such there is a pressing need in the industry for a reliable accurate predictive tool that can be used easily and in timescales appropriate for real engineering development and which delivers results that are discrete enough for conclusive structural investigations
  - In effect, the accuracy of the full 3D approach, but in timescales that enable this to be utilised at the concept and prototype phases
- Impossible……….?

WE'RE ALL IN IT TOGETHER

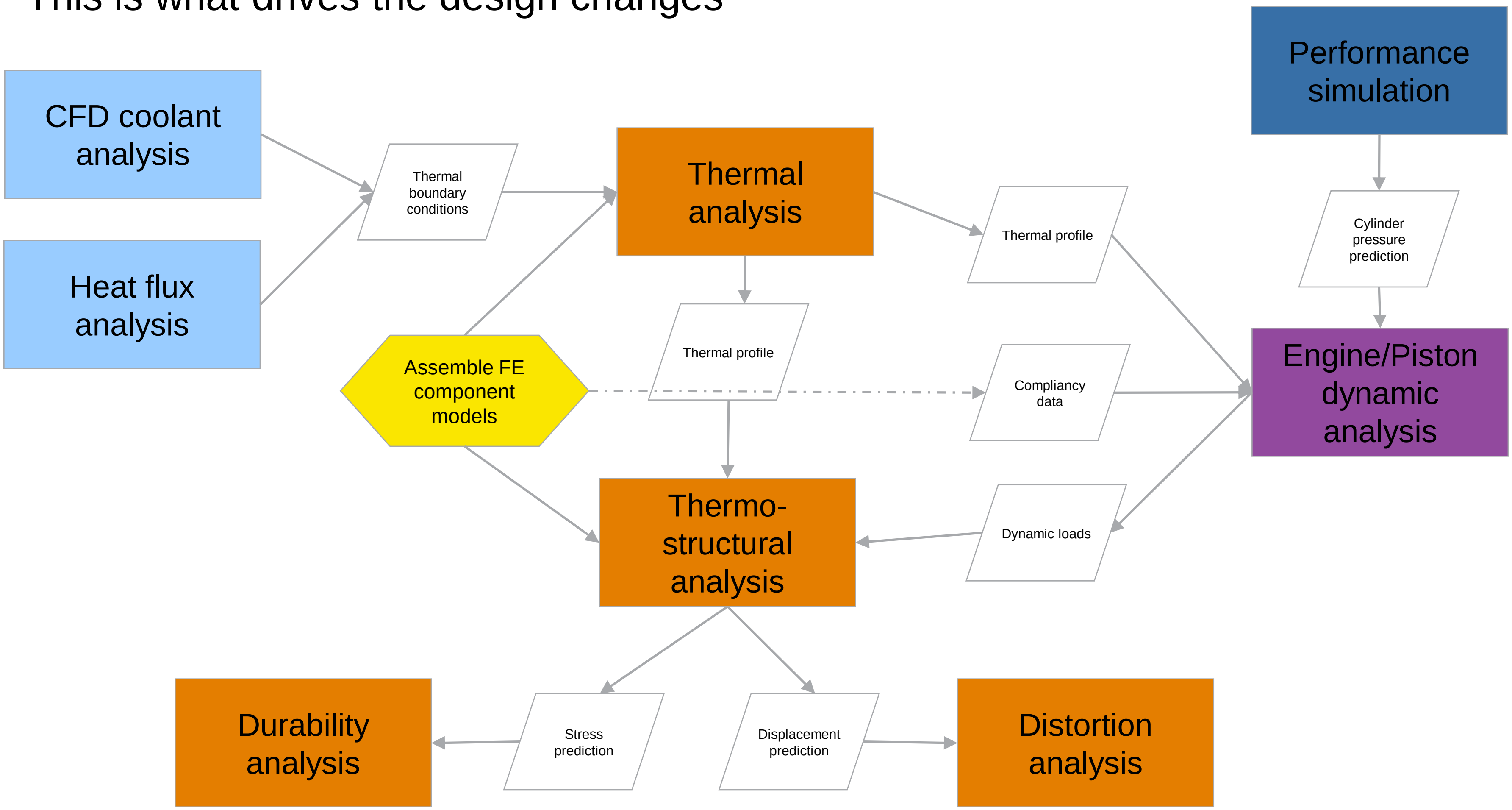
Taking an holistic view of the problem

- The general flow of a typical thermo-mechanical analysis looks like the diagram below
  - Here we are considering the tasks required for a cylinder block analysis



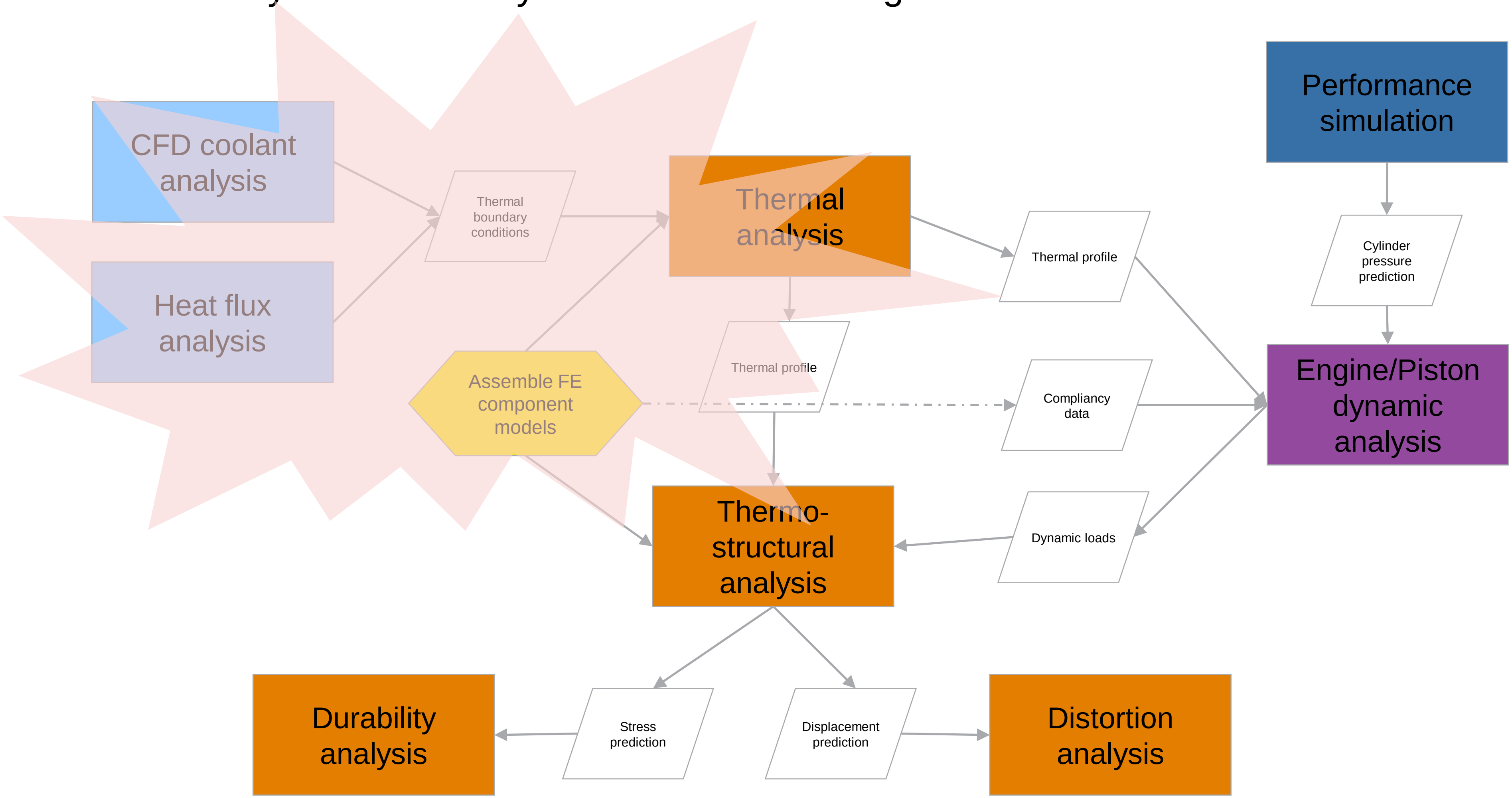
Taking an holistic view of the problem

- For the structural integrity, the key is to obtain accurate data on the distortion and durability of the system
  - This is what drives the design changes



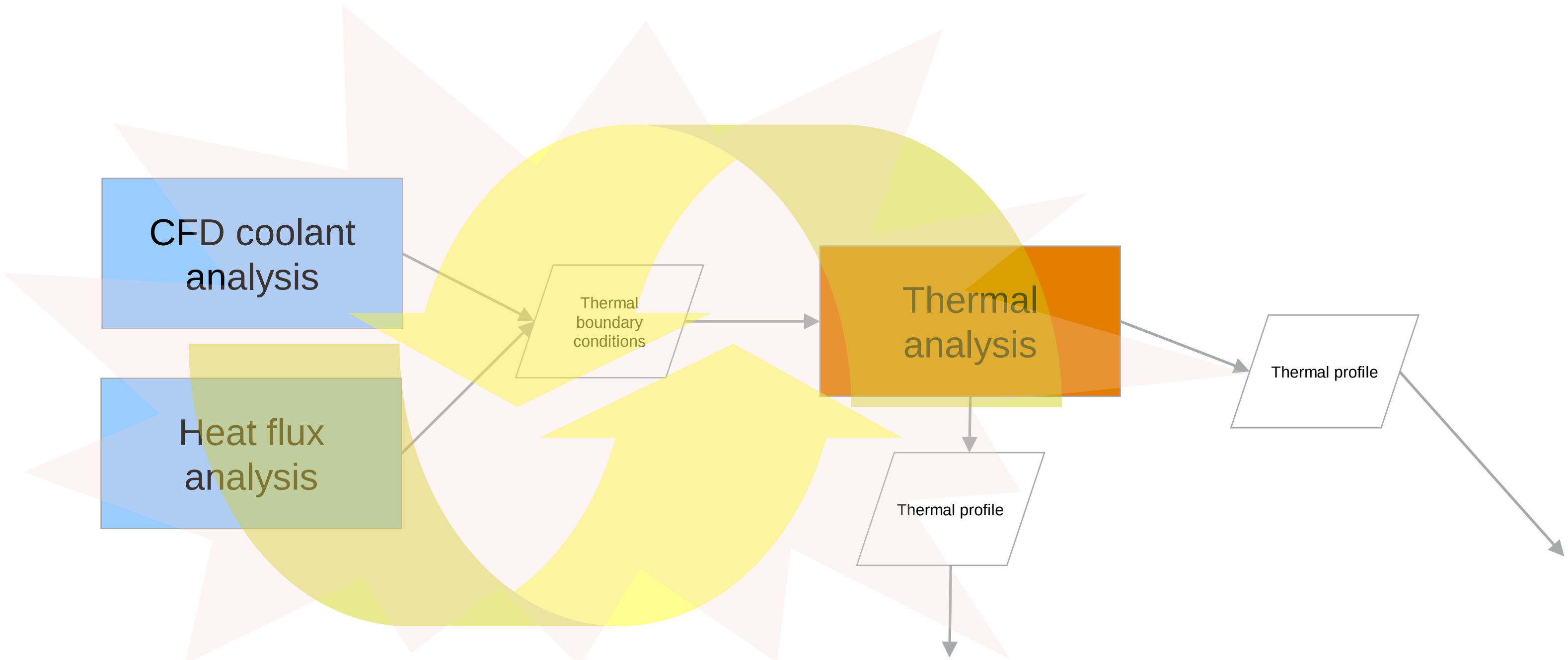
Fitting into the general workflow

- The map shows how critical the temperature prediction is to the system
  - This analysis must easily feed into a much larger workflow



The definitive requirement

- Isolating just the thermal prediction the tasks are as shown below



- **Key to an engineering process is getting *<u>appropriate</u>* thermal predictions downstream as quickly as possible to allow initial studies to be performed in other disciplines**

The definitive requirement

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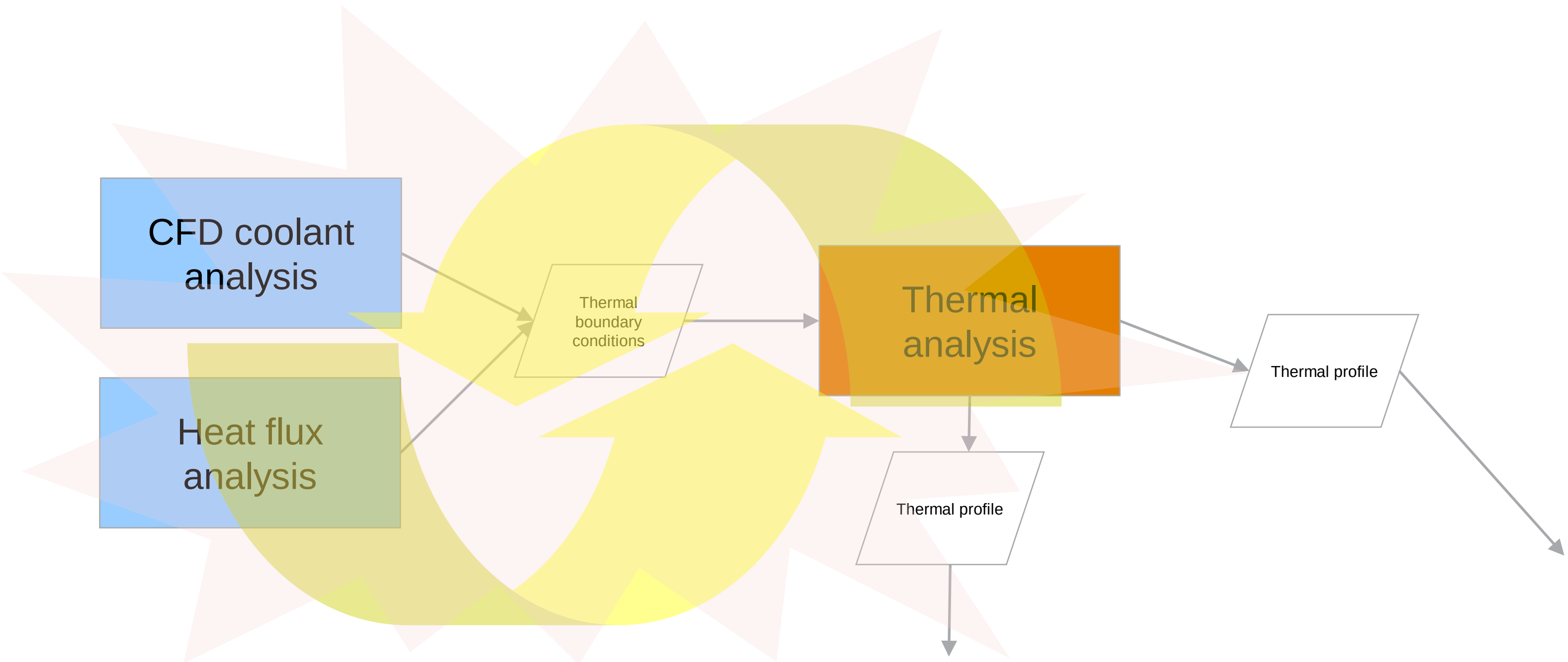

- **Key to an engineering process is getting *<u>appropriate</u>* thermal predictions downstream as quickly as possible to allow initial studies to be performed in other disciplines**
- At the concept stage accuracy can be sacrificed for absolute speed

The definitive requirement

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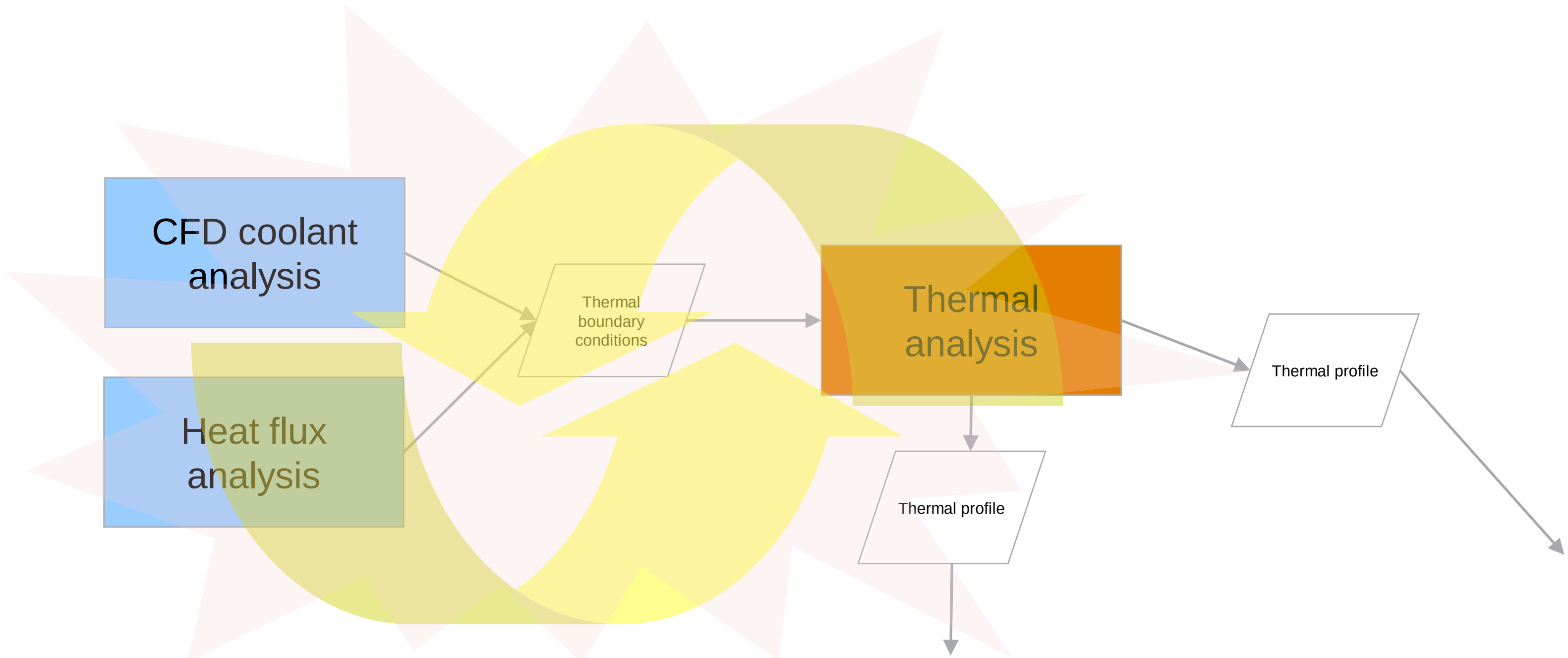
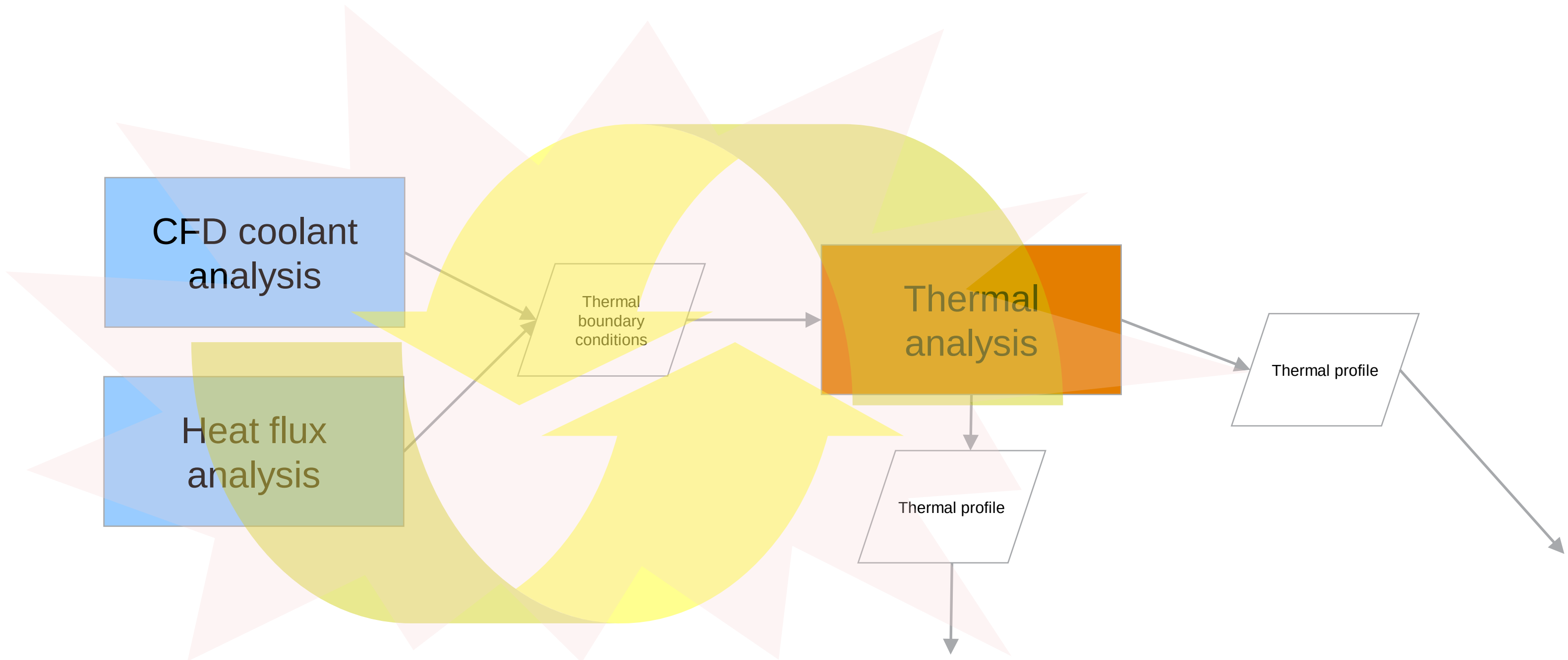


- **Key to an engineering process is getting *<u>appropriate</u>* thermal predictions downstream as quickly as possible to allow initial studies to be performed in other disciplines**
- A continuous flow of data through and around the process will allow for more definitive predictions to be made as the design progresses

The definitive requirement

- Isolating just the thermal prediction the tasks are as shown below



- **Key to an engineering process is getting *<u>appropriate</u>* thermal predictions downstream as quickly as possible to allow initial studies to be performed in other disciplines**
- Hence a fully integrated and holistic approach needs to be used to ensure engineers in different disciplines and domains are fully employed and driving the design on together

The definitive requirement

- So a real and complete engineering solution to the predictive analysis of the powertrain thermal distribution must achieve the following
  - **It must be able to utilise all levels of predictive methods and deploy them at appropriate times**
    - 1D and empirical methods at concept stage
    - 3D methods as early as possible
    - Continuously update and enhance the predictions whilst constantly feeding data into the wider analysis stream
      - and enhance the 3D predictions as the program progresses
  - **It must be fully integrated into the complete analytical and design process**
    - If the thermal prediction is isolated from the more general analyses required to identify performance, distortion and durability targets then there will be blockage and delay whilst waiting for this data to come through
    - If the thermal prediction becomes a specialised task in a single domain then there is an increased risk of the prediction becoming (remaining!) a research activity
      - And there will be no ability to employ cross domain solutions to design issues

THE RICARDO SOLUTION

The thermal prediction workflow

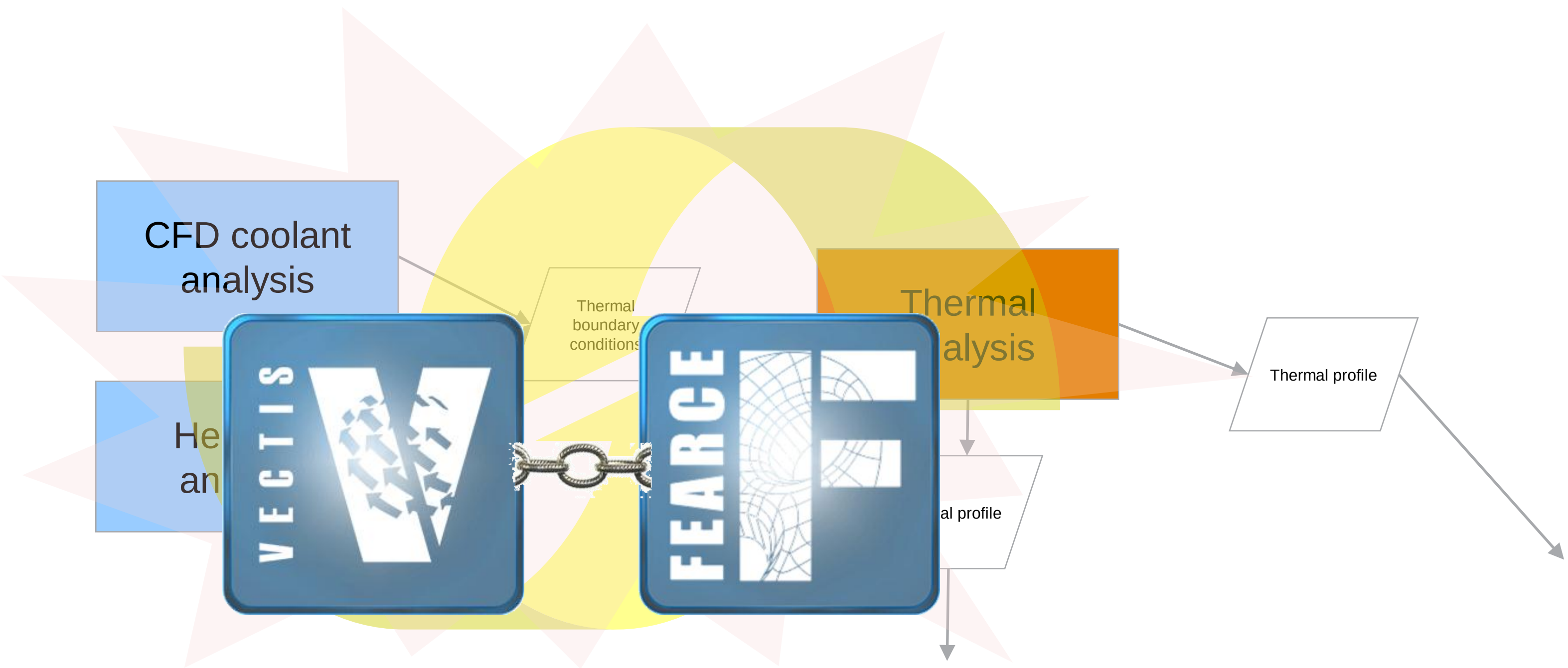
- It is clear then that a successful engineering solution to the thermal prediction workflow problem needs to deliver several key aspects
  - Lower fidelity heat flux prediction tools for early analyses
  - A fast, reliable and robust fully three dimensional combustion and coolant CFD tool
  - A seamless link to structural analysis tools and the ability to pass and manage vast quantities of data between different stages of the process
- In short, the most successful systems will take an holistic view of the whole engine system and deliver a comprehensive and fully integrated toolset
  - **…and Ricardo Software have every base covered**

The thermal prediction workflow

- Building upon the strengths of its dedicated powertrain CFD and FE tools, Ricardo have developed a comprehensive thermal prediction toolset designed to deliver reliably, robustly and repeatedly
  - **In real engineering workflows**
  - **In real engineering timescales**

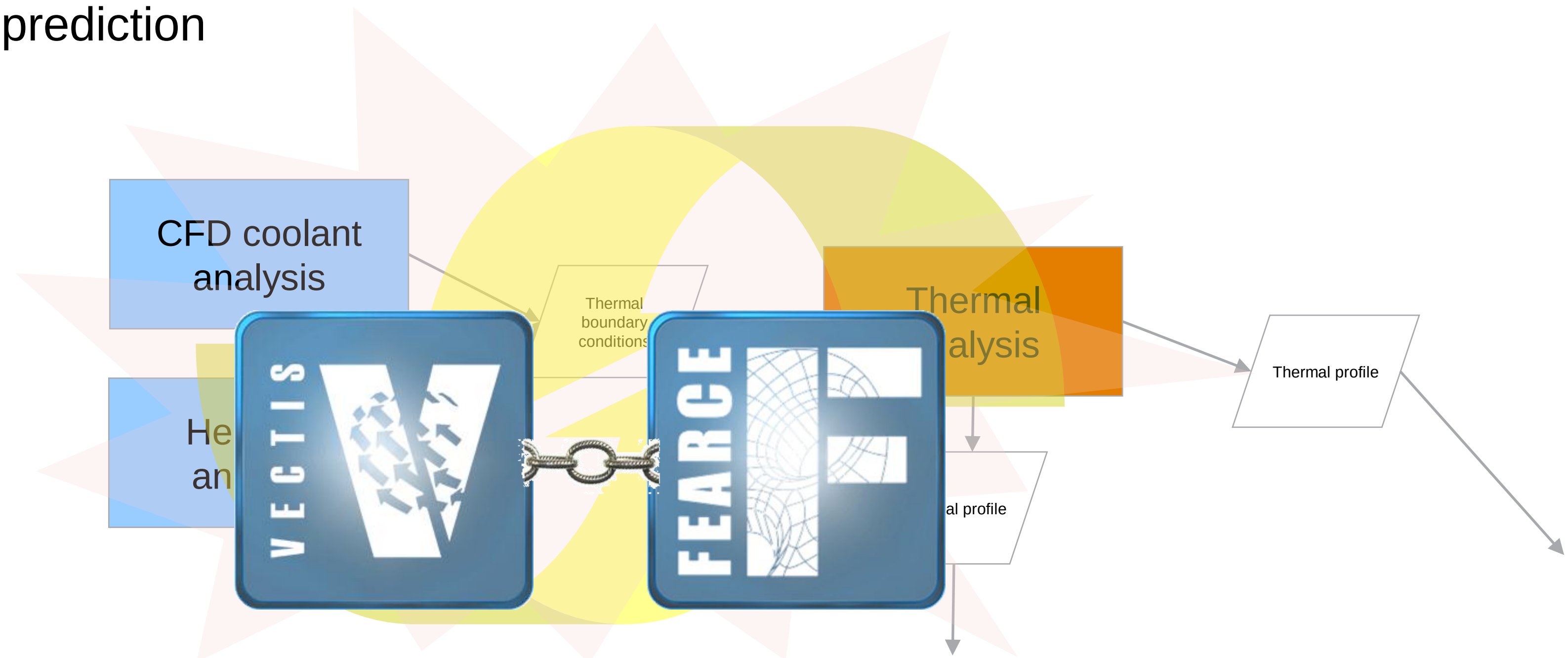
The thermal prediction workflow
The definitive requirement

- VECTIS and FEARCE work seamlessly together to provide a complete thermal toolset that bridge the divide between fluid and structural domains
- Managing solutions and data flow and breaking down barriers to true concurrent and developmental engineering



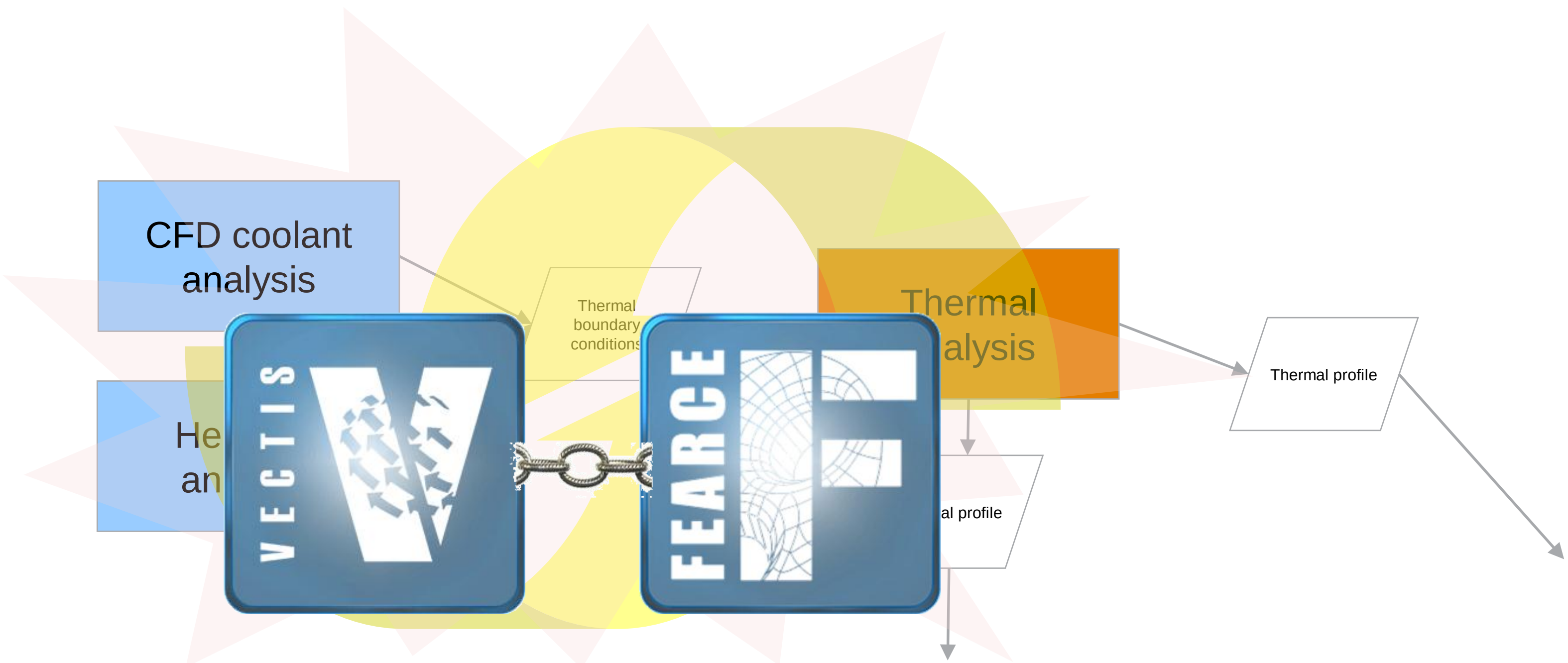
The thermal prediction workflow
The definitive requirement

- Offering best in class preparation and solution speeds for
  - Coolant analysis
  - In-cylinder combustion analysis
  - CHT thermal prediction
  - FE model preparation
  - FE thermal prediction



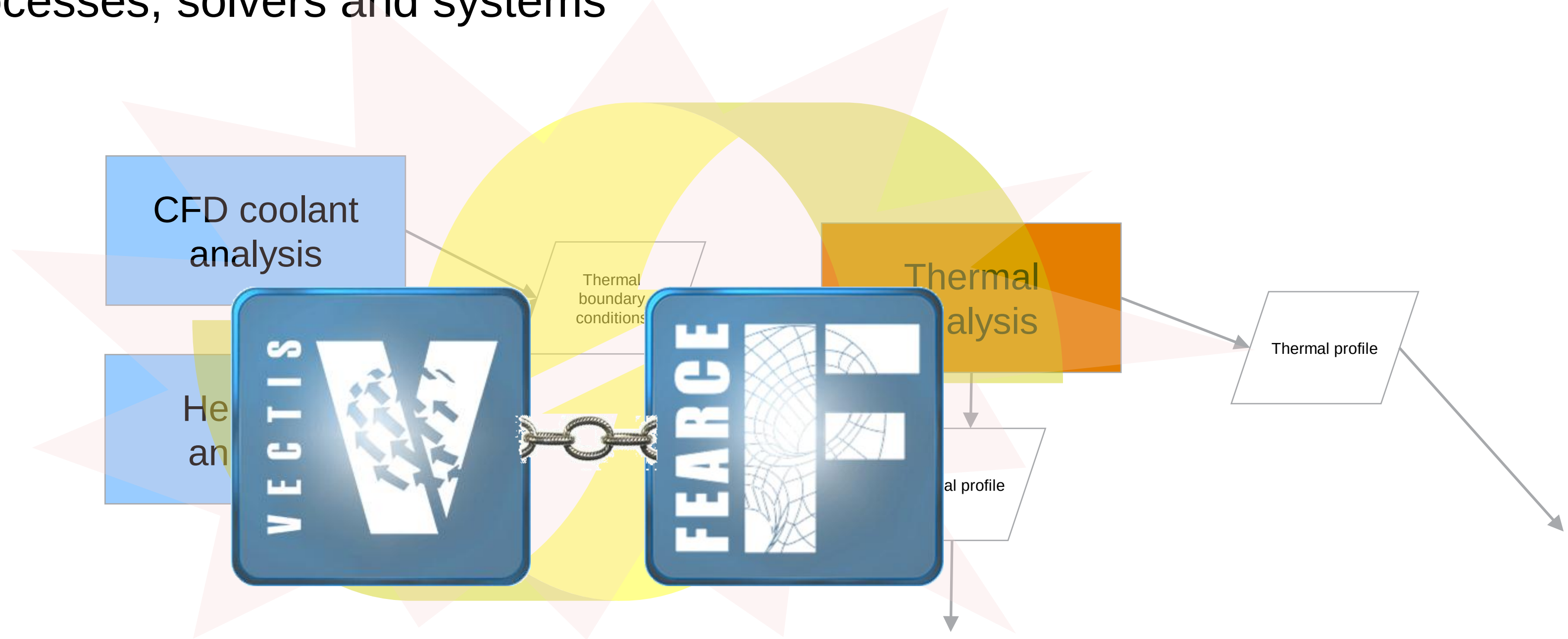
The definitive requirement
VECTIS

- Ricardo's VECTIS CFD tool is a dedicated CFD environment developed specifically to deliver results robustly and reliably
  - Optimising the preparation and solution to ensure the fastest turnaround times on any design



The definitive requirement
FEARCE

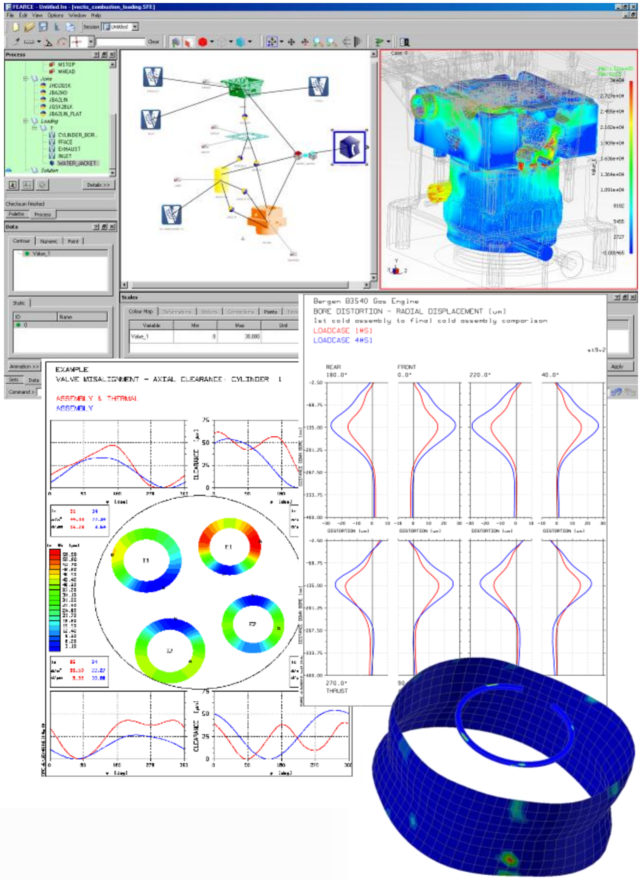
- Originally developed to manage Ricardo's finite element processes, FEARCE can link directly to the VECTIS CFD system to provide extended capabilities to the fluid dynamics solution whilst connecting these activities directly to the structural analysis environment
  - Ricardo's FEARCE tool is designed specifically to manage the complexities involved in large 3D analyses that necessitate a considerable in-flow and output of data from external processes, solvers and systems

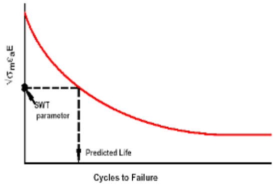


The definitive requirement
The VECTIS-FEARCE system

Detailed

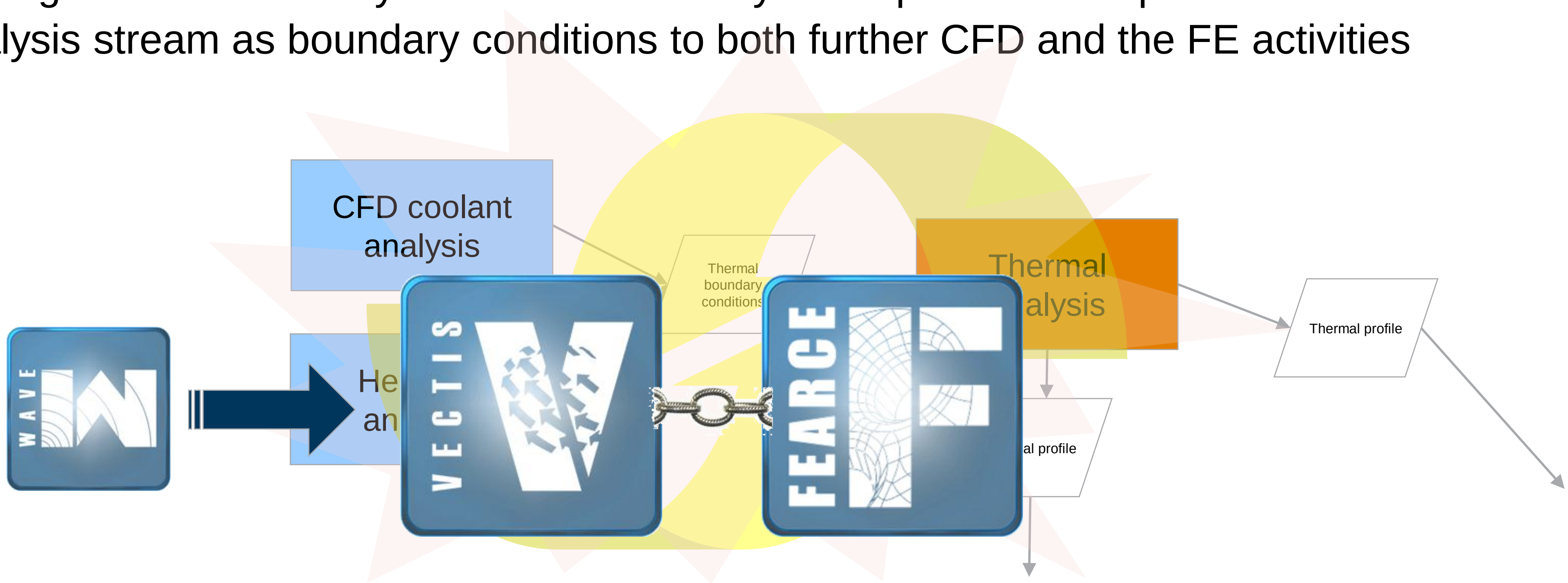
- By combining FEARCE with VECTIS the CFD calculation can be extended in a number of ways
  - FEARCE data management tools can be used to time average in-cylinder calculations and link them to CHT thermal solutions
  - FEARCE interpolation tools can be used to link CFD models and data to finite element systems
    - FE thermal solutions can then be used instead of CHT analysis providing more refined studies of heat paths through component interfaces
    - CHT thermal predictions can be passed to FE structural analyses either directly within FEARCE or to set up solutions in solvers such as ABAQUS, ANSYS or NASTRAN
  - FEARCE post processing tools can be used to provide structural results driven by thermal effects, such as
    - Detailed bore, valve guide and valve seat distortion, conformability and alignment analysis
    - Component displacement and stress analyses
    - Component durability analyses





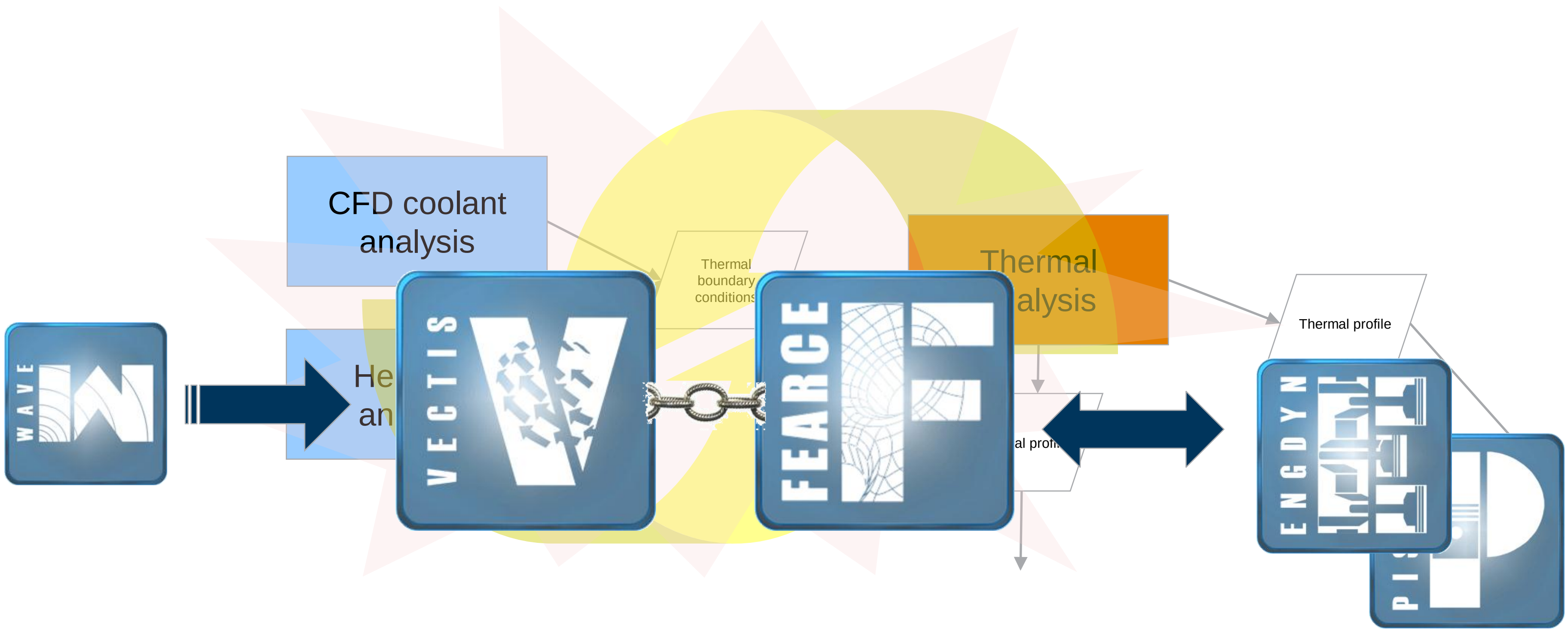
The definitive requirement
Different fidelities of combustion analysis

- The engine development and therefore the required tasks are based upon iterations of analyses with detail and fidelity increasing as the design matures
  - As such a comprehensive toolset will provide the user with a range of solutions allowing for early conceptual analyses to be performed and passed through the system without major changes to process or methodology
- Adding WAVE into the system allows for early concept data to be passed into the full analysis stream as boundary conditions to both further CFD and the FE activities



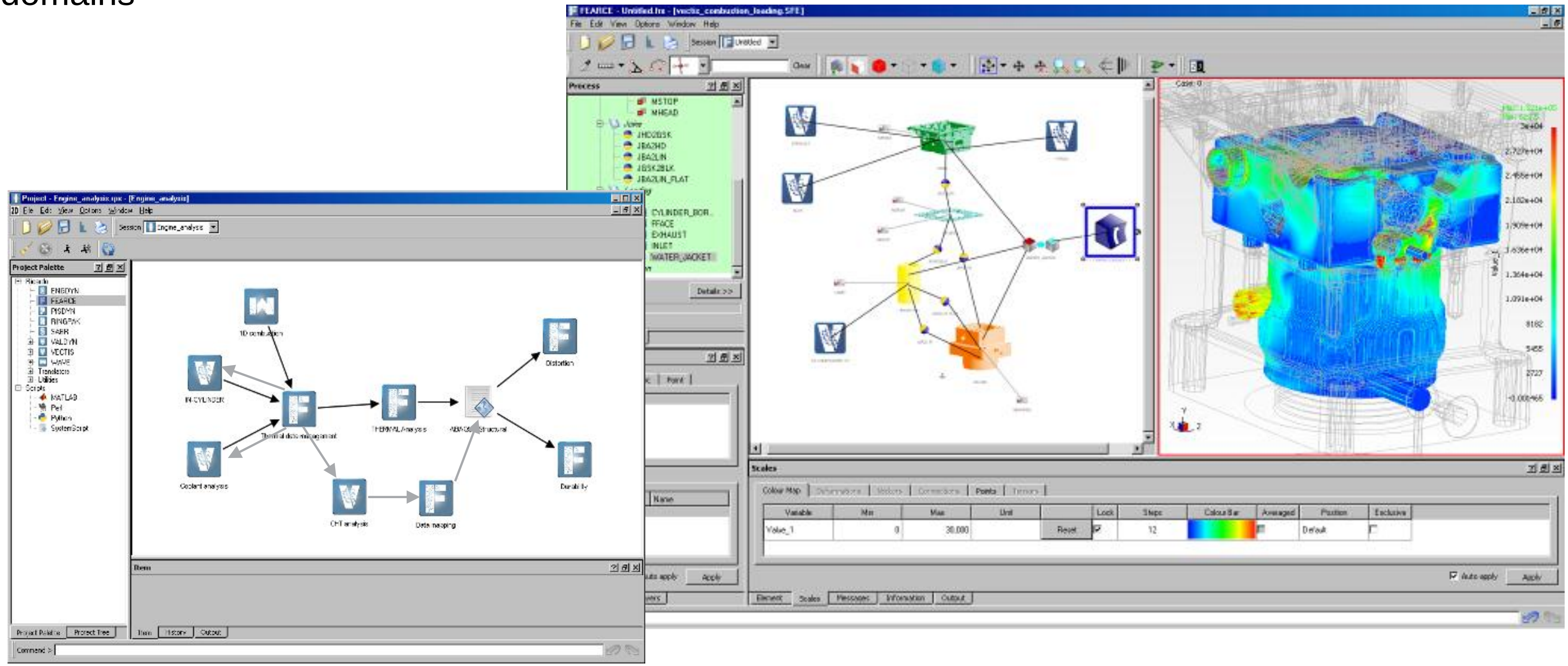
The definitive requirement
Working with the mechanical stream

- Structural solutions can be managed directly through the FEARCE process with the provision to directly add Ricardo's own dedicated mechanical dynamics simulation tools enhancing the calculation performance
  - The system also seamlessly fits into existing processes with links to ABAQUS, ANSYS, NASTRAN, ADVC and other 3rd party mechanical simulation packages



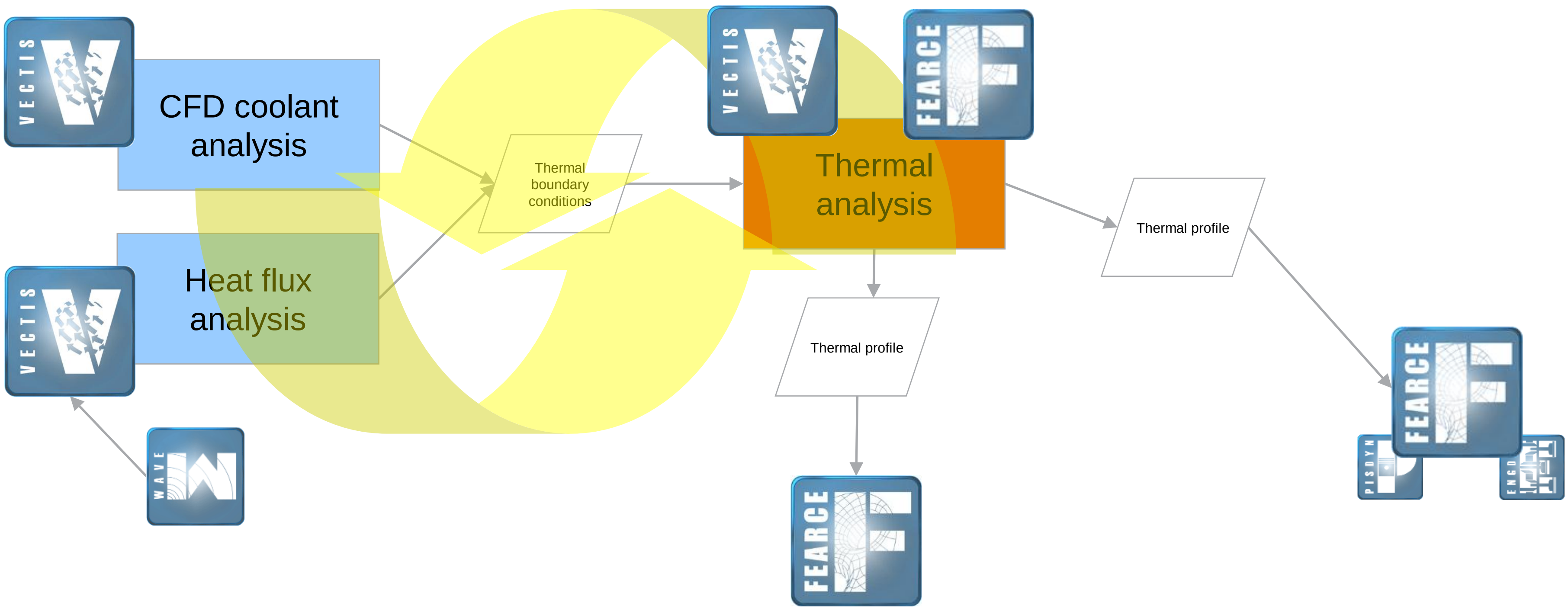
The definitive requirement
An integrated process …and an integrated environment

- Having all of the tools to provide a comprehensive solution is a major advantage
  - But Ricardo Software are going further and fully integrating the environment in which these are delivered
- With the new R-DESK GUI and the associated restructuring of Ricardo’s traditional packages, future delivery will be based upon fully integrated and coherent application based software across all domains



The definitive requirement
The Ricardo Solution

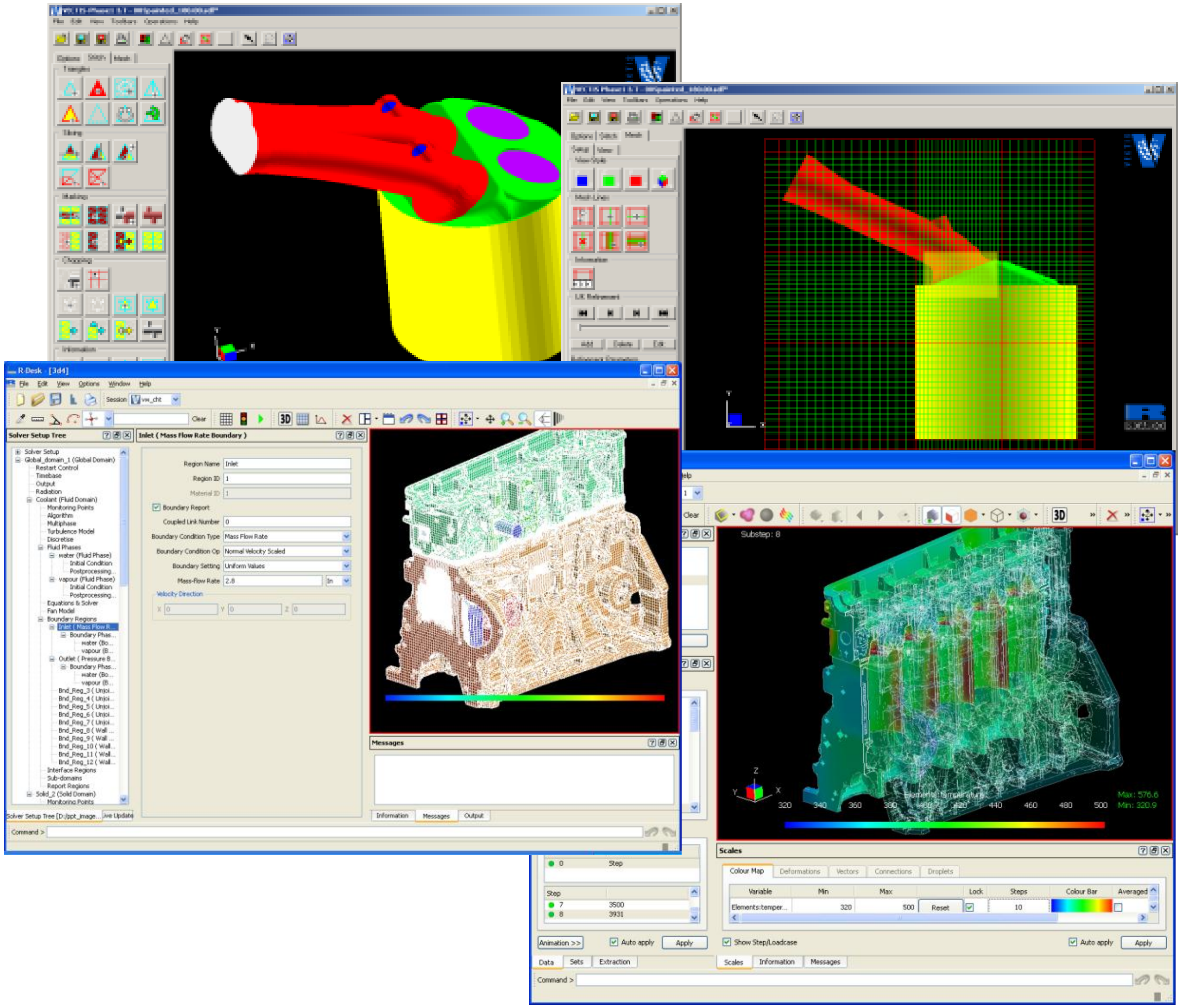
- The Ricardo thermal analysis system is based upon its 1D and 3D CFD tools linked directly to its own finite element environment FEARCE
  - This enables the full consideration of thermal boundary conditions
    - ….and successful delivery into the structural analysis chain
- **The impossible is now possible**



WHAT IS VECTIS?

What is VECTIS?

- VECTIS is a CFD code developed specifically to address fluid flow simulations in the vehicle and engine industries
- VECTIS includes:
  - Pre-processor
    - Geometry import and repair
    - Control mesh setup
    - Mesh viewing
  - Automatic mesh generator
  - Solver and solver setup GUI
  - Post-processor
    - Extensive visualization and data extraction capability
    - Ensight translator
  - VECTIS to FE data translators



What does VECTIS do?

Coolant flows

Spray modelling

Radiation

Port flows

Under hood

In-cylinder flow

Coupled

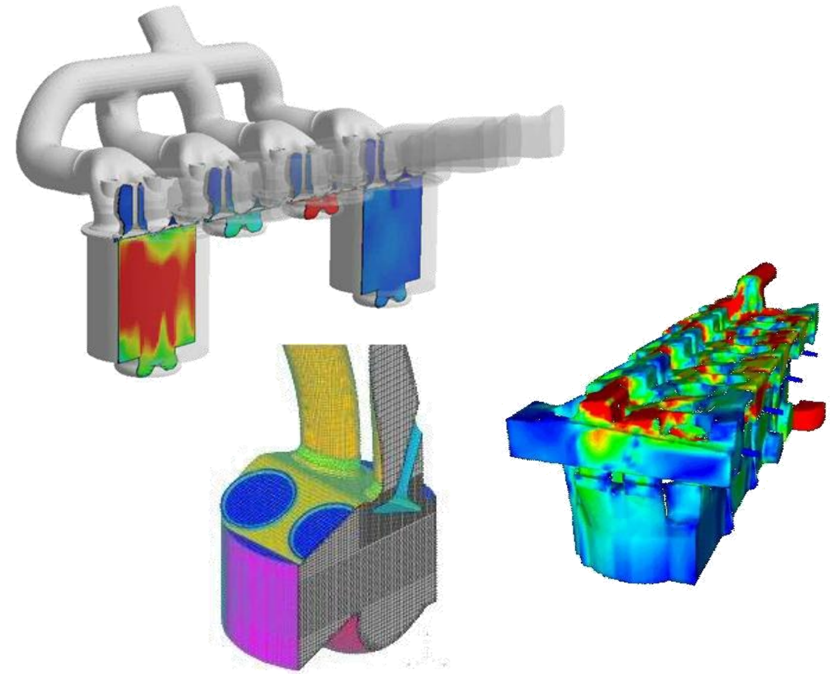
1D/3D

Combustion and emissions

Thermal analysis

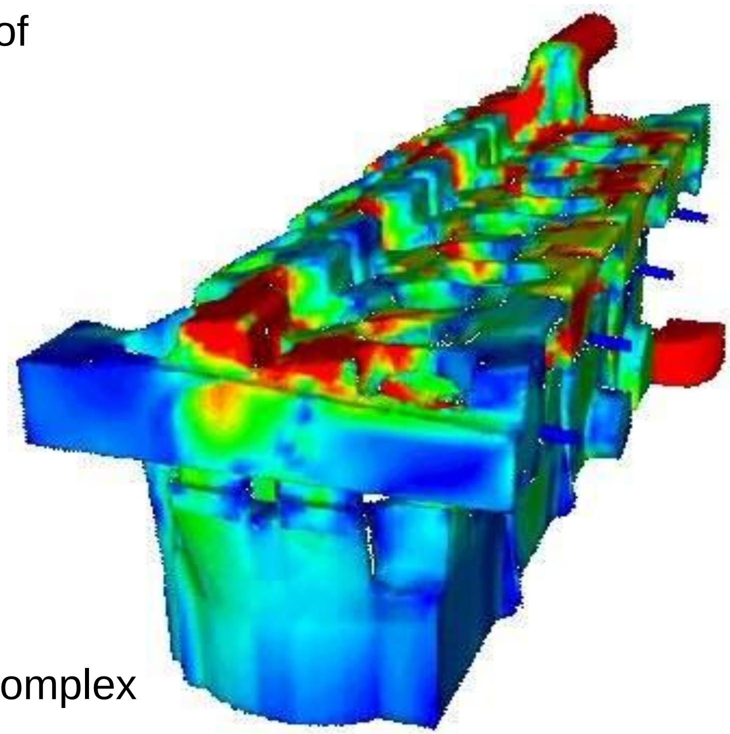
The VECTIS advantage
Dedication and speed

- Ricardo developed it's own CFD solver in order to improve the reliability and turnaround speed of powertrain specific analysis such as coolant flow and in-cylinder combustion prediction
- In addition to constantly improving solution times with more efficient models and techniques such as parallel analysis, a large emphasis has been placed upon reducing the time to get to the solver
  - Something that is often a problem with more general CFD tools and systems
- VECTIS incorporates automatic geometry repair and meshing tool enabling both static and moving boundary meshes to be created rapidly and easily
- With its industry leading CAD to results performance VECTIS was the obvious tool with which to develop a fast and accurate thermal prediction system



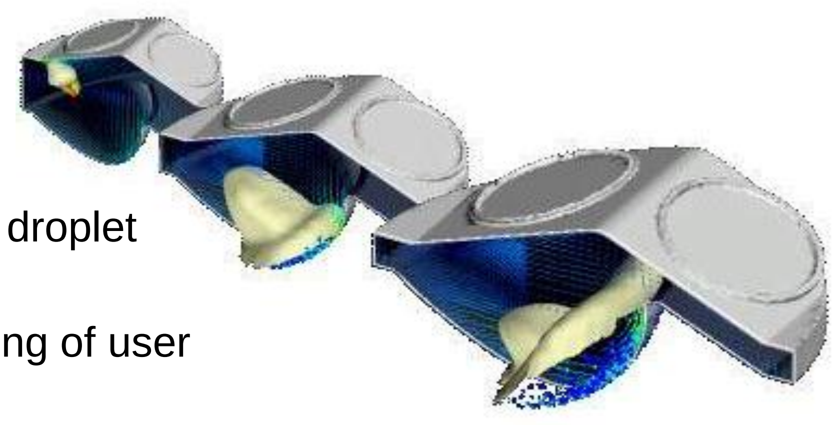
VECTIS
….keeping it cool

- VECTIS delivers a robust system for preparation and analysis of coolant flows
- Typical Engineering Use
  - Ensure effective cooling in critical areas
    - Sub-cooled nucleate boiling heat transfer included
  - Optimize head gasket designs and transfer passages
  - Ensure cooling imbalance between cylinders is minimal
  - Reduce cooling jacket overall pressure drop
  - Investigate warm up times
- VECTIS Advantages
  - Automatic meshing capability particularly beneficial due to complex water jacket shapes
  - Boiling model allows for prediction of boiling and resulting heat transfer effects
  - Best in class CAD to result turnaround time



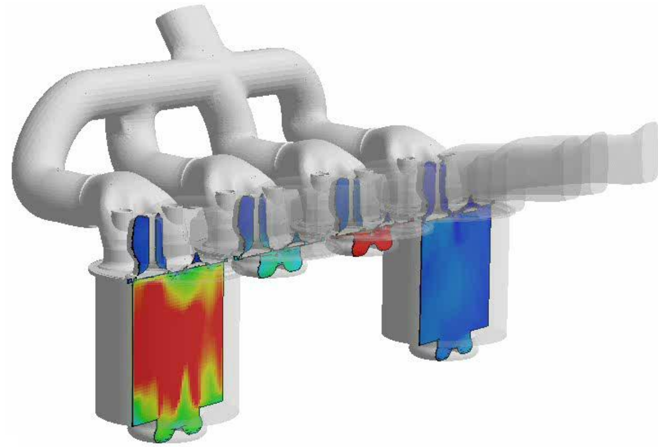
VECTIS
Spray modeling

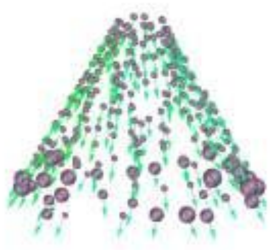
- Typical Engineering Use
  - Model port injection or direct injection sprays
- VECTIS Advantages
  - Discrete droplet modeling for sprays
    - Primary and secondary breakup models as well as droplet interaction
    - Extensive user function capability allows for modeling of user defined injector configurations
  - Static and dynamic wall film capability
    - User function initialisation and data extraction capability
  - Multi-component fuels
  - Nozzle to discrete droplet primary breakup model

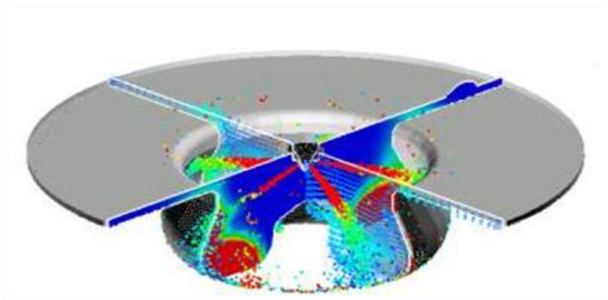


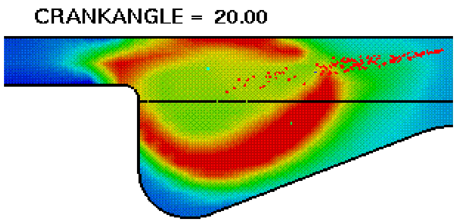
VECTIS
…..in the cylinder

- The typical engineering uses for in-cylinder analyses are
  - Investigate air, fuel and combustion product species motion
  - Model port injection or direct injection sprays
  - Optimise combustion process
- VECTIS Advantages
  - Moving boundary and automatic meshing technique provides easy setup
    - Multi-cycle, multi-cylinder calculations
  - Discrete droplet modeling for sprays
  - Static and dynamic wall film capability
  - Auto-ignition and spark ignition models
  - Ricardo Two Zone Flamelet combustion model
  - Multiple Interactive Flamelet combustion
  - G-equation for pre-mixed combustion
  - Links to Ignition Progress Variable Libraries
    - for HCCI, Premixed and non-premixed combustion
  - Extensive internal validation programs



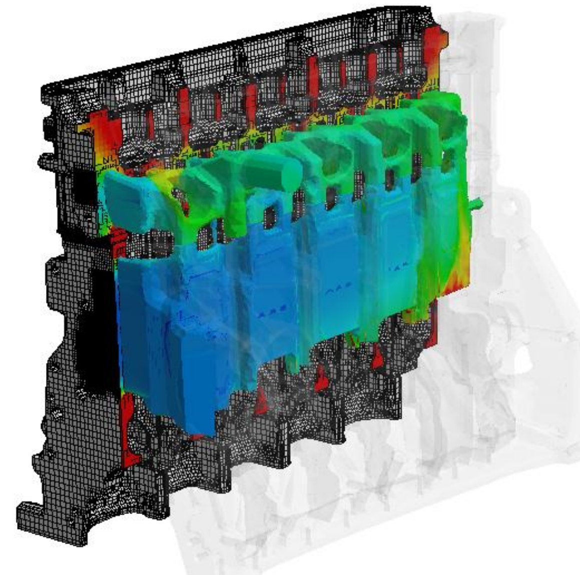


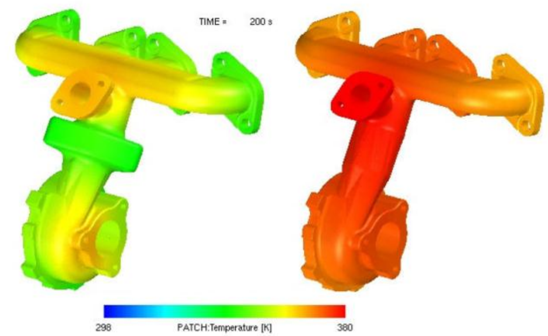


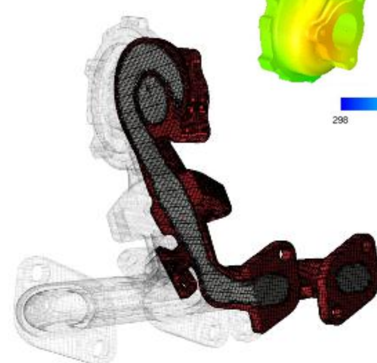


VECTIS
Conjugate Heat Transfer Analyses

- Typical Engineering Use
  - Intelligent cooling system development
  - Fluid and solid components modeled
    - fluid flow, solid thermal distribution, boundary heat transfer
    - components such as the engine block and cylinder head
    - Transient thermal predictions for warm-up
- VECTIS Advantages
  - Multi-domain solver solves Solid and Fluid domains implicitly
  - Automated conformal meshing of multi-domain cases (solid/fluid)
  - Extensive tools to set up detailed external boundary conditions
  - Boiling model allows for prediction of boiling and resulting heat transfer effects
  - Direct export of CFD results for use in FE structural analyses



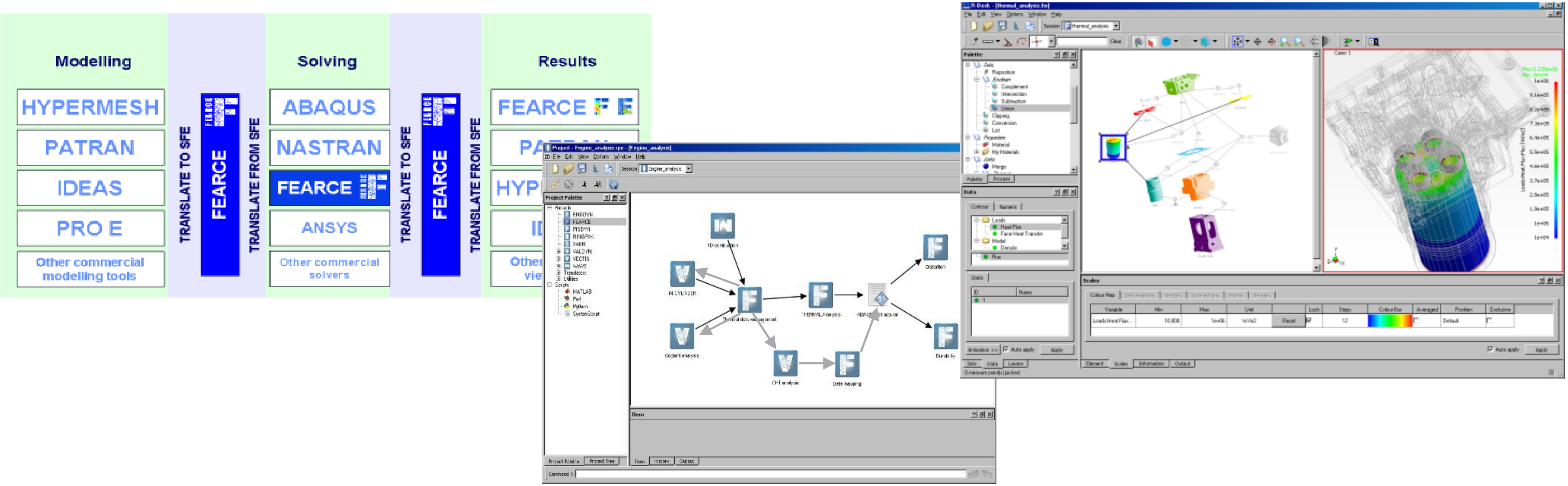




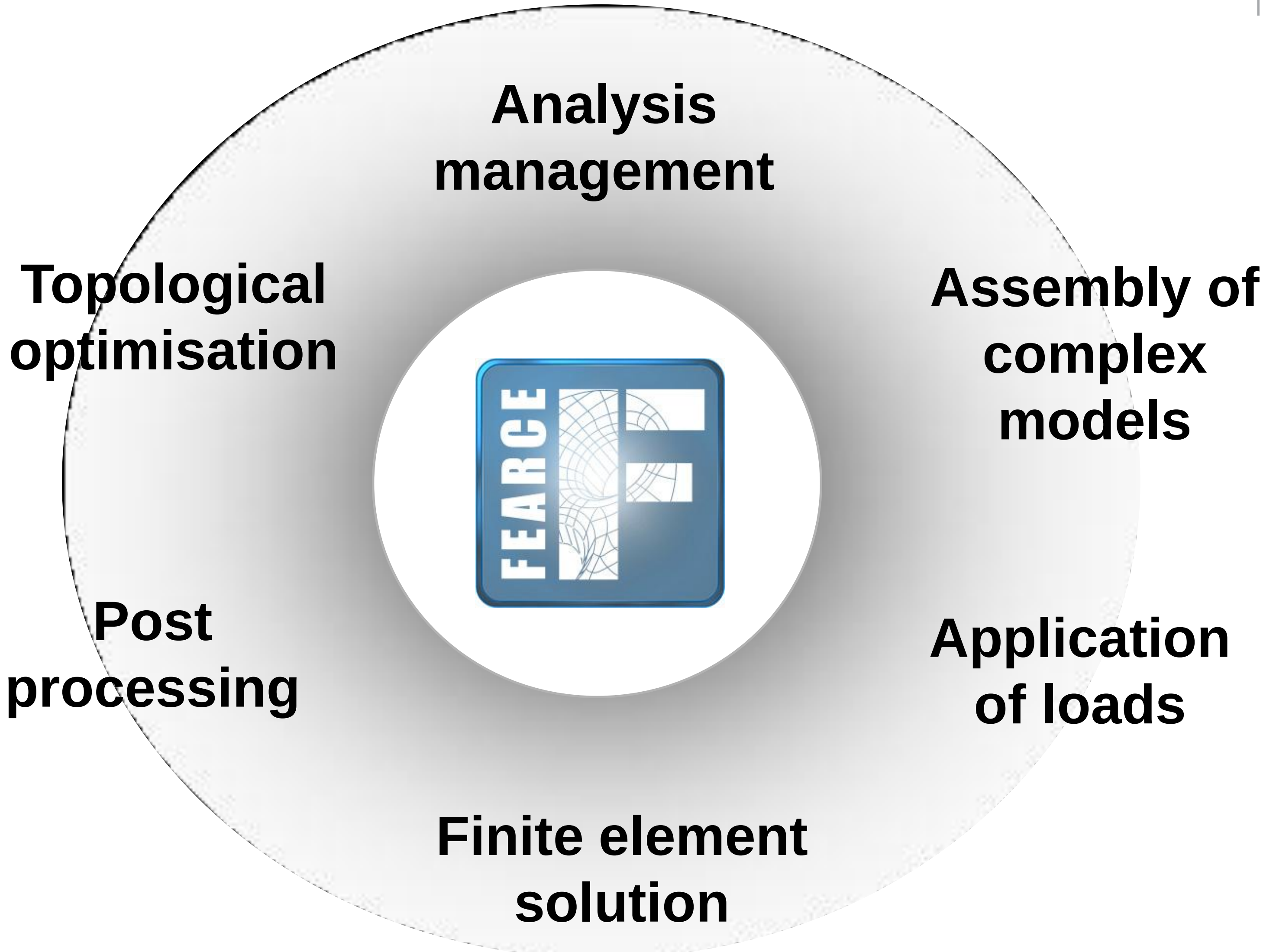
WHAT IS FEARCE?

What is FEARCE?

- FEARCE is a finite element pre and post processing package written specifically to support engine and vehicle analysis which has been used at Ricardo for over 20 years
- FEARCE acts as an interface to integrate each stage of a finite element analysis (FEA)
  - From the assembly of component models into larger systems
    - Through the application of loads and boundary conditions from a variety of sources
      - To the solution and post-processing of results
- FEARCE adds automation to these key tasks so that complex analyses can be performed quickly and accurately whilst ensuring common processes are identical between iterations

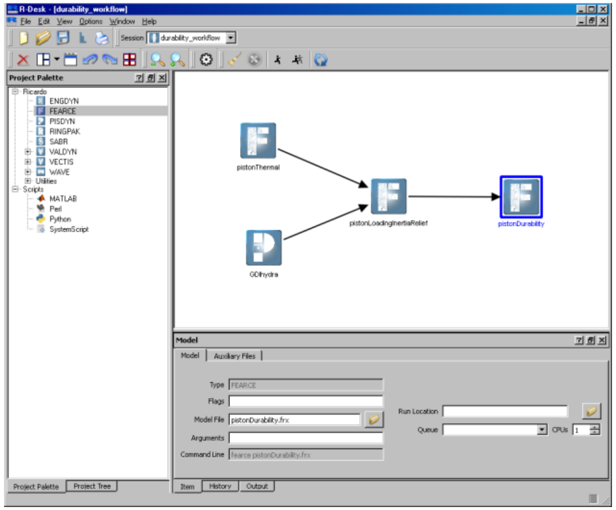


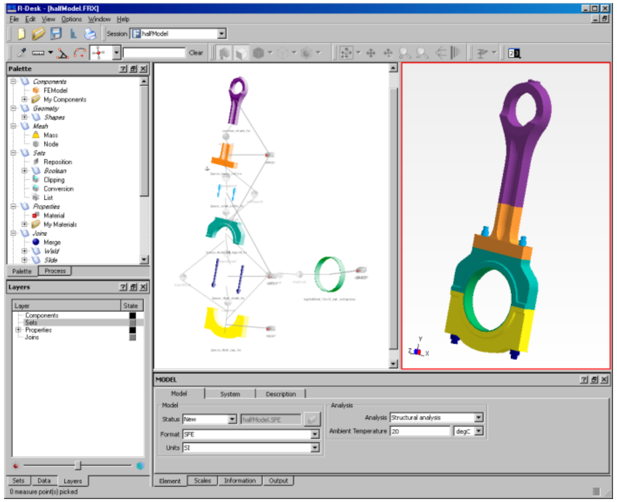
What does FEARCE do?



What does FEARCE do?
Analysis management

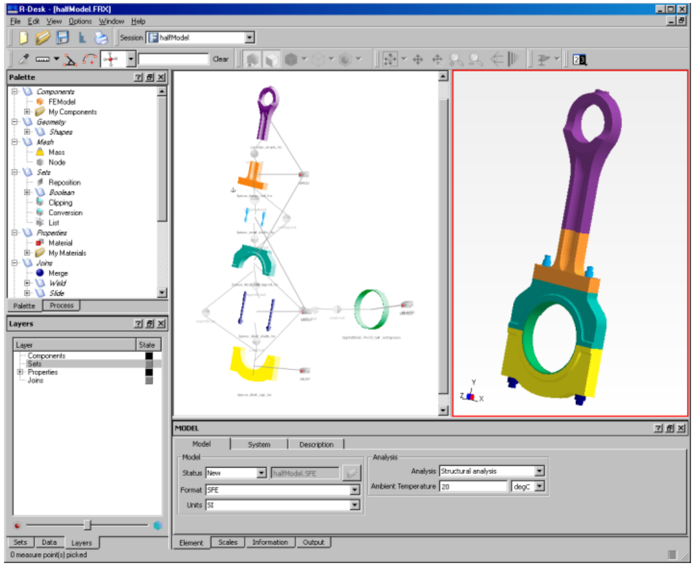
- Common applications:
  - Setting up and running whole analysis workflows using the top level Project tool
    - Several analyses using various tools can be linked together into a continuous workflow
    - Dependencies are handled through the Project
    - All Ricardo products fully linked
      - Third party software can be linked through run scripts
  - Setting up and managing complex finite element assemblies
    - Component parts selected through a parts store
      - Each part easily replaced for iterations
    - Joins and loads defined within the process and easily modified without changing mesh

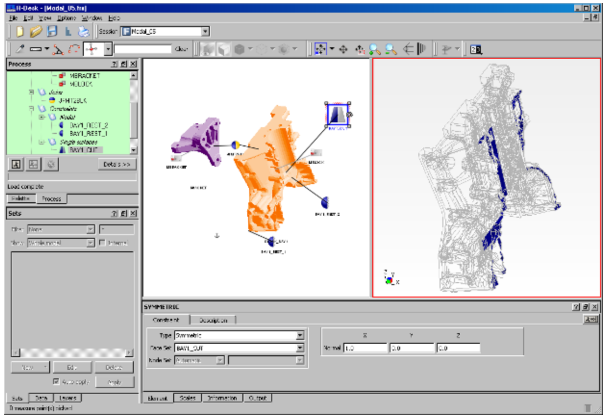




What does FEARCE do?
Assembly of complex models

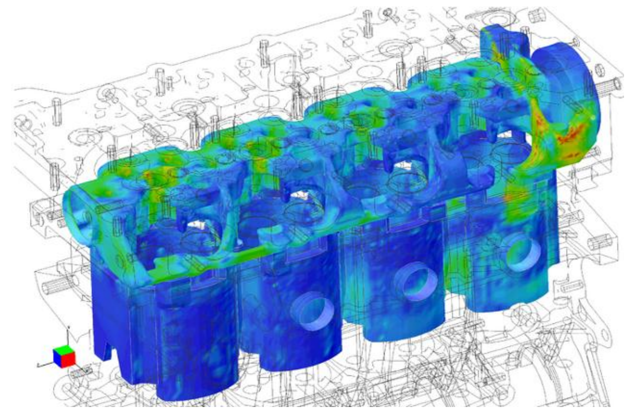
- Technical features:
  - Automated tools for the joining of non matching meshes between component models
    - No reliance on matching nodes or pre defined node numbers
      - User simply specifies the surfaces to be joined
    - Numerous types of joins can be generated including
      - Weld, slide, contact, thermal and structural gaps
    - All standard mesh types supported
    - Automatic checking of joins with conflicts, fixes and warnings flagged
  - Single and multi surface constraints easily applied by simply specifying the surfaces and type of constraint required
    - Often used to define physics on cut planes for models representing sections of an assembly
  - Simple FE models automatically generated from geometric definition
    - E.g. bolts, bearing shells, primitive shapes

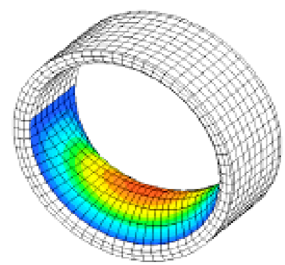


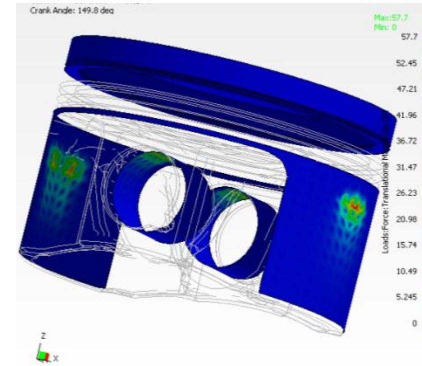


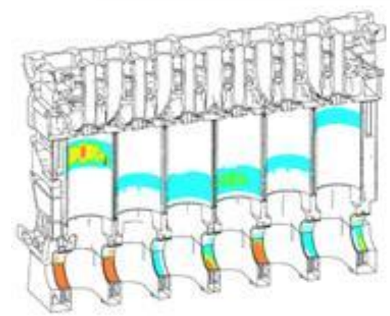
What does FEARCE do?
Application of loads

- Common applications:
  - Linking data from various sources to manage complex FE projects
    - Interpolation of CFD results onto FE models
      - Direct link to VECTIS
    - In a similar way data can be extracted and applied from ASCII files containing no more than nodal co-ordinate and associated data
    - Mapping of complex mechanical loads onto FE assemblies directly from dynamic solvers
      - VALDYN, PISDYN and ENGDYN
  - Applying correctly distributed bearing loads across loaded surfaces
    - Bearing model just requires maximum load bearing type and reference to the loaded surface
  - Automatic generation and loading of bolts in FE assemblies



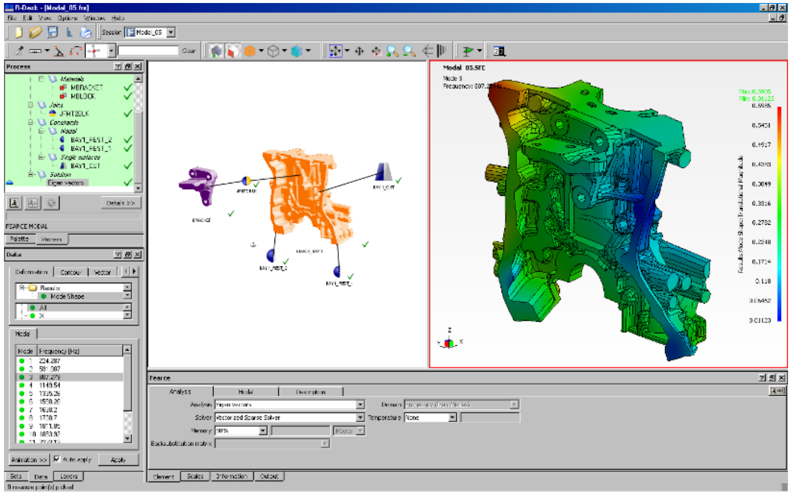


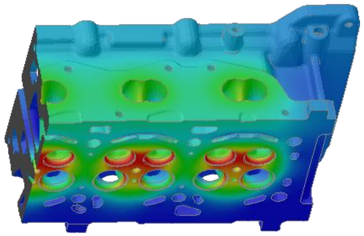


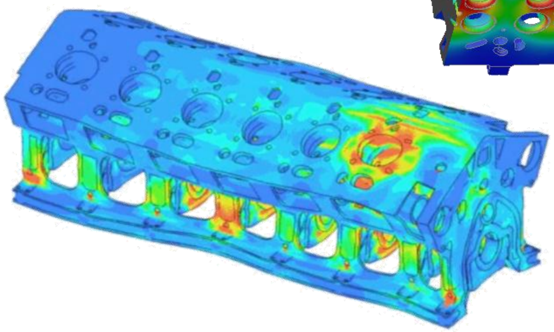


What does FEARCE do?
Finite element solution

- Common applications:
  - All common solutions supported
    - Either directly through FEARCE linear solver
    - Or linking to major third party solvers for non linear and advanced solutions
  - Typical linear solutions handled directly include
    - Thermal analysis
    - Linear displacement and stress
    - Strain energy analysis
    - Modal frequency analysis
    - FE model reduction
      - Static and dynamic
  - Links to third party solvers including
    - ABAQUS, ANSYS, ADVC and NASTRAN

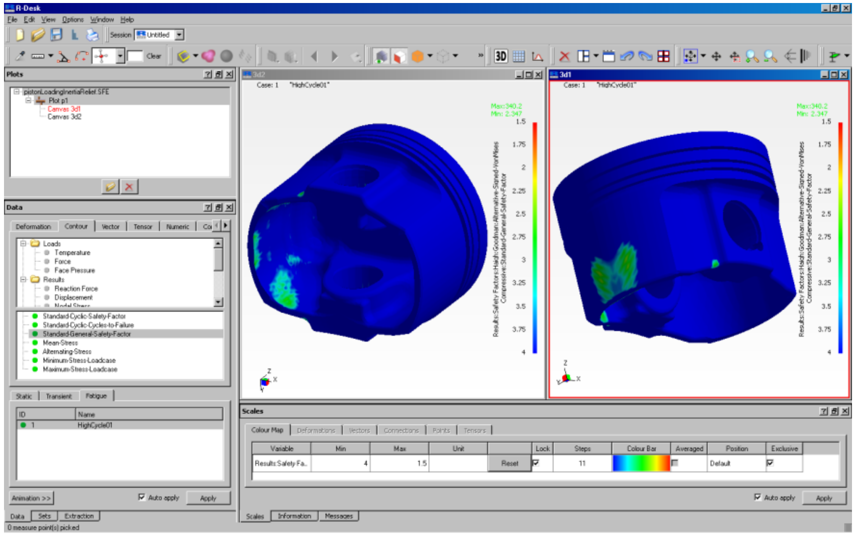


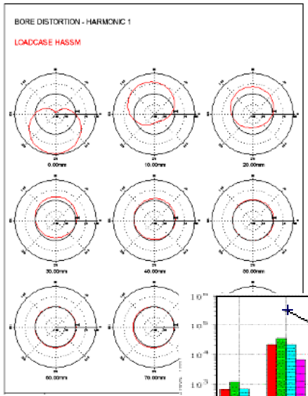


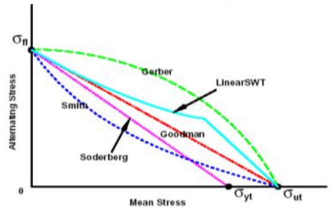


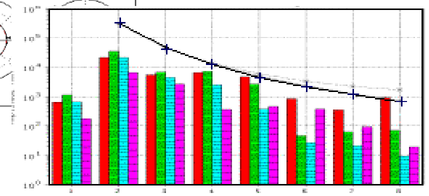
What does FEARCE do?
Post processing

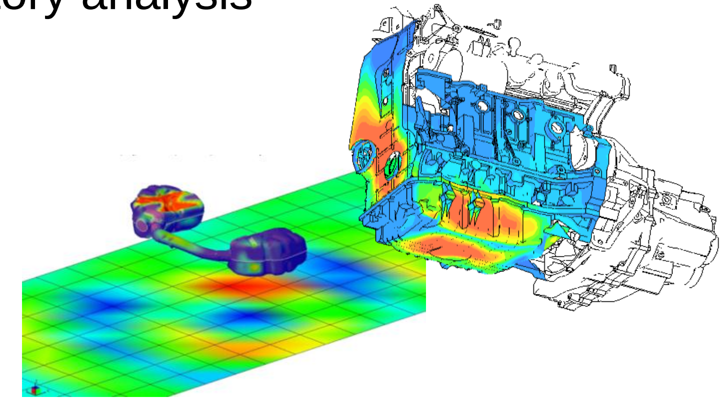
- Common applications:
  - Visualisation of results
    - 3D plotting and animation
    - Extraction of data
    - 2D plots
  - Bore, bearing and valve distortion analysis
    - Distorted shape, harmonics and alignment
  - Results combination and factoring
  - Thermocouple and strain gauge plots
  - Stress and strain history analysis
  - Durability analysis
  - NVH analysis











DETAILED METHODOLOGY

Process options
Thermal analysis in VECTIS: Conjugate heat transfer (CHT)

- The first option is to perform the metal temperature within the VECTIS solver using the CHT method
- The combustion analysis is performed separately and then used as a boundary condition to a coupled fluid/solid solution where the cooling effects of the fluids are solved in tandem with the metal temperatures
  - The combustion analysis will be time averaged over one engine cycle. This time averaged data will be mapped to the CHT analysis
  - There is also a requirement to be able to easily map the final results onto FE meshes for further analysis
    - FEARCE will be used to perform these two tasks

This method is currently used in VECTIS

- Advantages
  - Implicit solving between the fluid and solid domains
  - Ability to incorporate boiling effects within the coolant
  - CFD trained engineers will be familiar with the whole process
  - The decoupling of the coolant and combustion analyses allows for data to be generated at different stages of the development process

Process options
Thermal analysis in VECTIS: Conjugate heat transfer (CHT): Coupled

- In the second method, a variant of the CHT option, the coolant and combustion analyses can be fully coupled so that data is passed on each time step
- The FE link is then used at the end of the calculation to apply the temperature distribution to the FE model system for further analysis
- Advantages
  - The coupling allows for transient analyses to be performed in order to model effects such as warm up and cool down

This method is currently being finalised in the VECTIS/FEARCE system

Process options
Thermal analysis in FEARCE: FE thermal analysis

- The third option is to perform the thermal analysis within the FEARCE environment using an FE thermal analysis
- The combustion analysis and coolant analyses are performed within VECTIS and then passed onto the FE model as boundary conditions
  - There is a requirement to perform a time averaging of the combustion analysis and map this to the FE model
  - There is also a requirement to be able to easily map the boundary conditions onto the FE models
    - FEARCE is used to perform these two tasks and then carry out the thermal solution
- Advantages
  - FEARCE FE solver is very fast
  - Allows fine control of heat transfer between key sold components such as the valve seats and for pressure dependent heat transfer paths to be calculated iteratively with a structural analysis
  - Provides data into the development process as early as possible
  - Allows FEARCE to be used to link with PISDYN to provide rigorous calculations for the heat transfer between the liner through the rings and skirt of the piston assembly

This method is currently available in the VECTIS/FEARCE system

Process options
Fully coupled CFD – FE thermal analysis

- The fourth option is to perform a crank angle coupled solution using both the CFD and FE environments
  - VECTIS is used to calculate the coolant systems heat transfer coefficients
  - VECTIS then performs the in-cylinder combustion analysis and passes the result to FEARCE at each time step
  - FEARCE combines the coolant and combustion loads at the time-step and solves for metal temperature
  - This temperature is passed back to VECTIS for the next crank angle combustion solution
- Advantages
  - Utilises the fast FE solver with the added ability to include CFD boiling and transient effects
  - Enables the use of fine control over heat transfer between key components
  - Enables the heat flow between the liner and piston skirt to be calculated
  - By fully linking both the CFD and FE components both sets of engineers are working from the same system saving time on analysis and data transfer

This method is planned for development in the VECTIS/FEARCE system

Now and next

- The basic process is now in place
- Ricardo are currently undertaking a major validation exercise to benchmark the VECTIS in-cylinder approach against test data for a wide range of engine types
- The study is also comparing total set up and analysis times against accuracy for the empirical, 1D and fully 3D methods
- Work to improve the current system is largely based upon usability and interface
  - Tasks include
    - Modifications to time averaging algorithm
    - Improved interpolation routines
    - Developing Project management tool
    - Automating iterations
    - Reducing data storage overheads
    - Speeding up mapping process