CCP-WSI OpenFOAM Parallel Performance Engineering Workshop

Developing Dynamic Load Balancing with OpenFOAM

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The CCP-WSI Project

The CCP-WSI Project

Project Overview

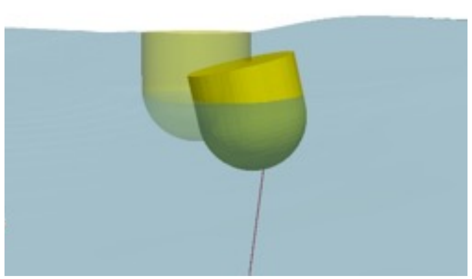
* 1st October 2015 – 30th September 2025 (2 phase 10 years)
* Funded by the Engineering and Physical Sciences Research Council (EPSRC)
* CCP-WSI Working Group – 6 UK-based research institutes
* CCP-WSI Advisory Group – over 30 project partners

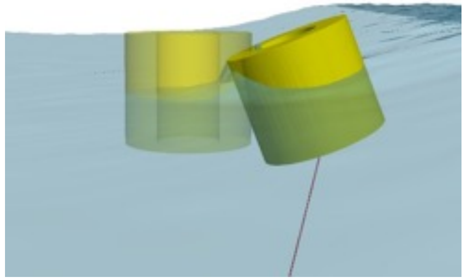
Objectives

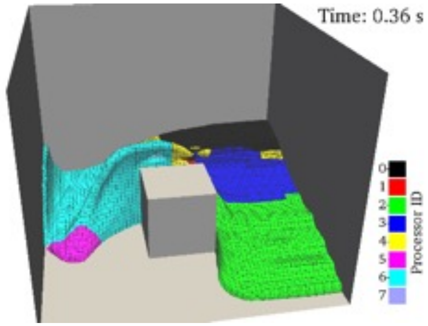
1. Build and grow a community of researchers, data, code and expertise
   - Across a wide range of disciplines/fields and internationally from both academia and industry
   - Including: database of benchmarking test cases and a repository of open-source software
   - With the shared objective of building a future-proofed and maintainable NWT facility
2. Bring together experimentalists, computer scientists and CFD engineers
   - Allow development of and sharing of ideas and processes for numerical modelling and validation
3. Provide advanced training in computer science and software development
   - Best practise guidelines: code development, characterising data, verification and validation processes
   - Outreach activities for schools and the general public
4. Provide a framework/focus for innovation and development of strategic software
   - Driven by networking activities and focus group workshops
   - Road mapping exercises to inform CCP-WSI strategy

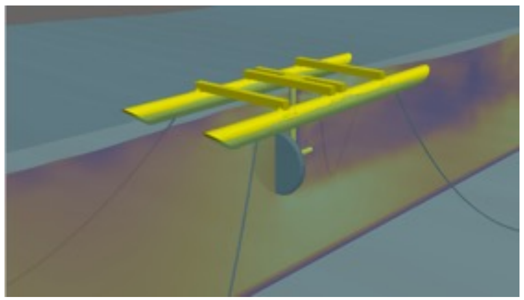
Introduction

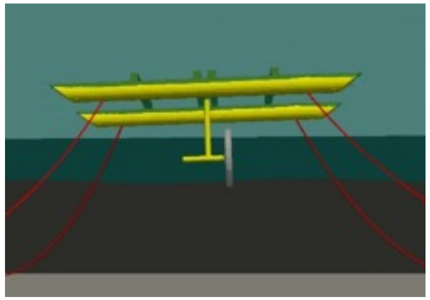
- Motivation
  - Examples of WSI problems
  - wsiFoam
- OpenFOAM optimization for HPC platform
  - Aims and objectives
  - Porting and verification of wsiFoam
  - Mesh Decomposition
  - Dynamic Load Balancing Library
  - Results and performance analysis
  - GPU dev
- The CCP-WSI Project
  - Code repository











Motivation and Examples of WSI Problems

Motivation and Examples of WSI Problems

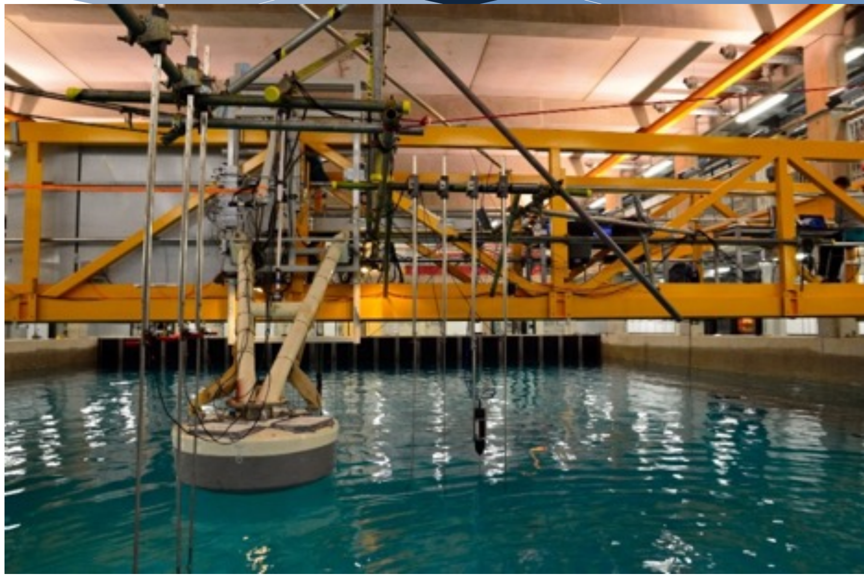
Survivability of WECs

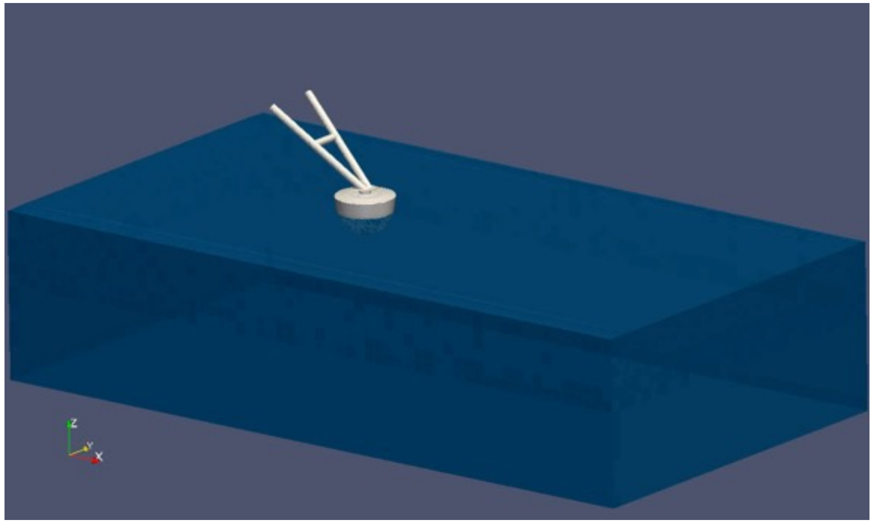
NEW CODE

- Numerical wave makers
- Focused wave generation using waves2Foam
- New ‘restraints’ for moored WECs
  - Coupled PTO model

CASES

- Fixed truncated circular cylinder
- Moored hemispherical bottomed buoy
- The Wavestar machine
- The Seabased Wave Energy Converter





Ransley, E. J., **Greaves, D.** M., Raby, A., Simmonds, D., Jakobsen, M. M., Kramer, M. 2017, RANS-VOF modelling of the Wavestar point absorber, Renewable Energy, 109, pp 49-65

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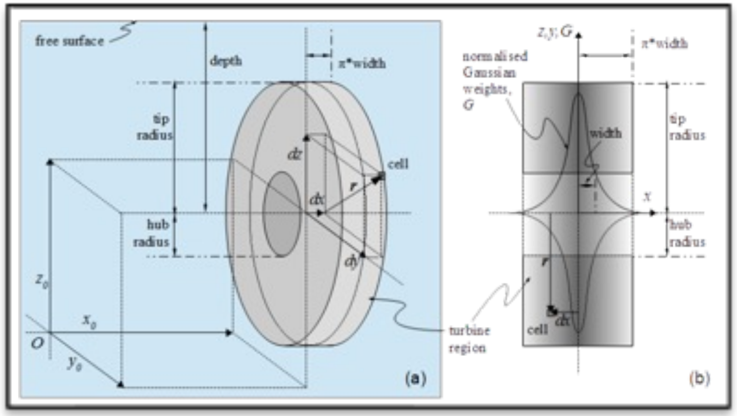
Floating Tidal Stream Concepts (iUK102217)

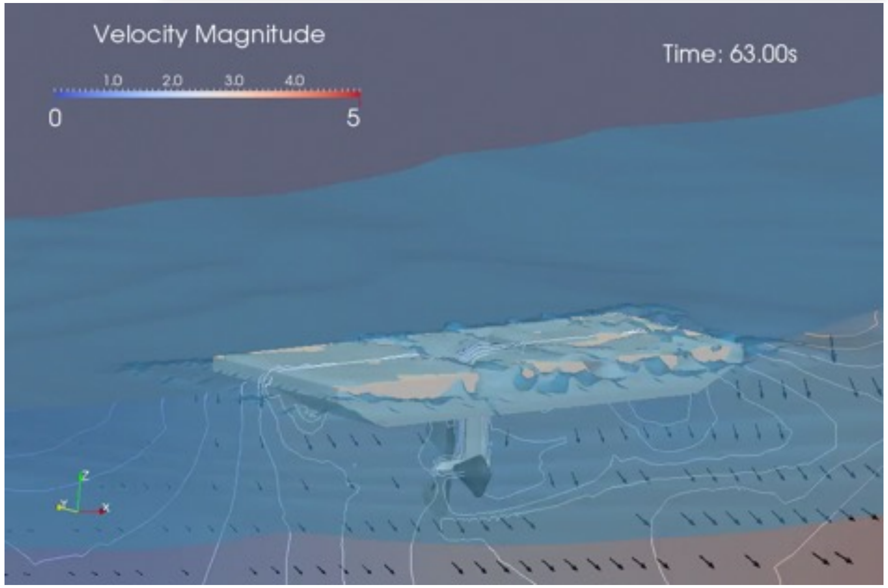
NEW CODE

- New libraries allowing for applied body forces
  - Turbine classes - analytical & real turbine data
  - Multiple turbines
    - Any number, size, orientation…
- Coupled turbine models with rigid body solver
  - Body motion ↔ turbine thrust
    - Turbine position up-dated at run-time
  - Turbine thrust ↔ fluid velocity
    - Additional source term in U equation
- Mooring models
  - Based on Orcaflex outputs

CASES

- MTG Tidal Raft Platform Concept





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MODULAR TIDE GENERATORS LIMITED

mojo

A&P

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Innovate UK Technology Strategy Board

Ransley et al. 2016, 'Coupled RANS-VOF Modelling of Floating Tidal Stream Concepts', in Proceedings of the 4th Marine Energy Technology Symposium, April 25-27, 2016, Washington ,DC

Motivation and Examples of WSI Problems

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Floating Tidal Stream Concepts (iUK103499)

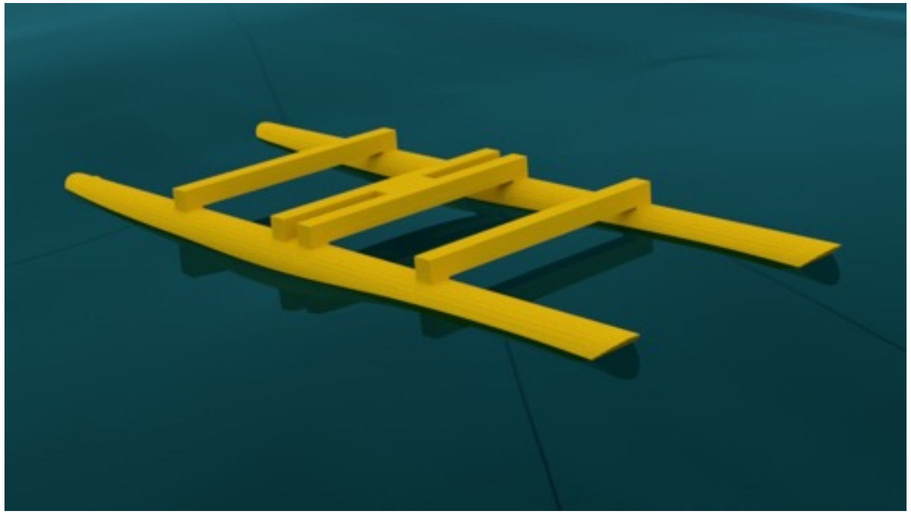
CODE

- Coupled rigid-body solver and turbine model
- Catenary mooring code

CASES

- MTG Tidal Raft Platform Concept

Ransley et al. 2018. Concept development for deployment of a modular, floating, tidal-stream device, in Guedes Soares (Ed.), Advances in Renewable Energies Offshore: 175-180, Taylor & Francis Group, London, ISBN 978-1-138-58535-5



Xie et al. 2018. Wave tank experiments of a floating, tidal-stream energy device, in Guedes Soares (Ed.), Advances in Renewable Energies Offshore: 203-207, Taylor & Francis Group, London, ISBN 978-1-138-58535-5.

Motivation and Examples of WSI Problems

FROTH (EP/J012866/1)

NEW CODE

- Extreme wave generation boundary conditions added to waves2Foam (OpenFOAM)
  - Focused wave group (NewWave)
  - Second-order Stokes theory
- Hydroelasticity/FSI – elastic body deformation

CASES

- Focused wave interaction with an FPSO
- Cylinder in heave and heave & pitch motion
- Fixed and floating moored FPSO (6DOF)
- Extreme wave impact on a hull
  - Slight breaking, flip-through, large air pocket, broken wave
- Wave impacts on a 'flexible' vertical wall

Hu et al. 2016, 'A Numerical and experimental Study of a Simplified FPSO in Extreme Free Surface Waves', in Proceedings of the 26th international Offshore and Polar Engineering Conference, June 26 – July 2, 2016, Rhodes, Greece

Mai, T., Hu, ZZ, Greaves, D and Raby, A. (2015) Investigation of Hydroelasticity: Wave Impact on a Truncated Vertical Wall, ISOPE, 2015, Hawaii.

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UNIVERSITY OF BATH
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Motivation and Examples of WSI Problems

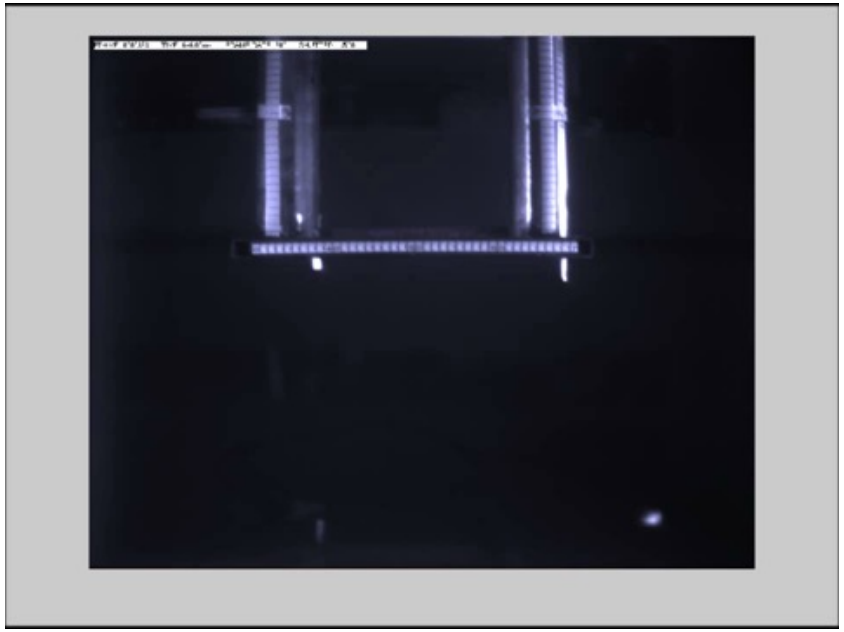
FROTH (EP/J012866/1)

NEW CODE

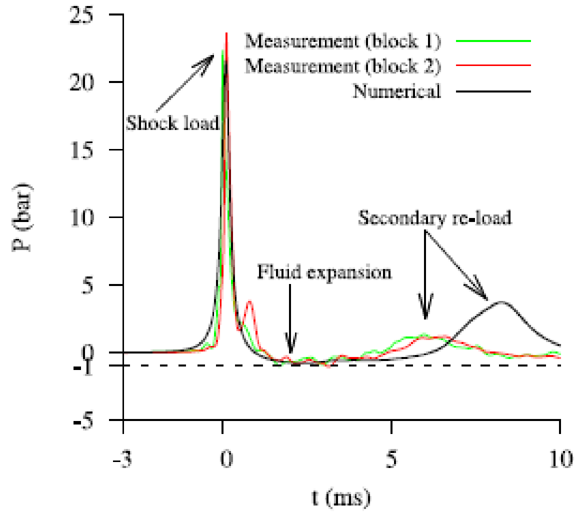
- Compressible air and water/air bubble mixture model

CASES

- Drop test into pure and aerated water
- Slamming loads on a flat plate



Ma, Z. H., Causon, D. M., Qian, L., Mingham, C.G., Mai, T., Greaves, D. and Raby, A. 2016
Pure and aerated water entry of a flat plate, Phys. Fluids 28, 016104 (2016);
http://dx.doi.org/10.1063/1.4940043



Motivation and Examples of WSI Problems

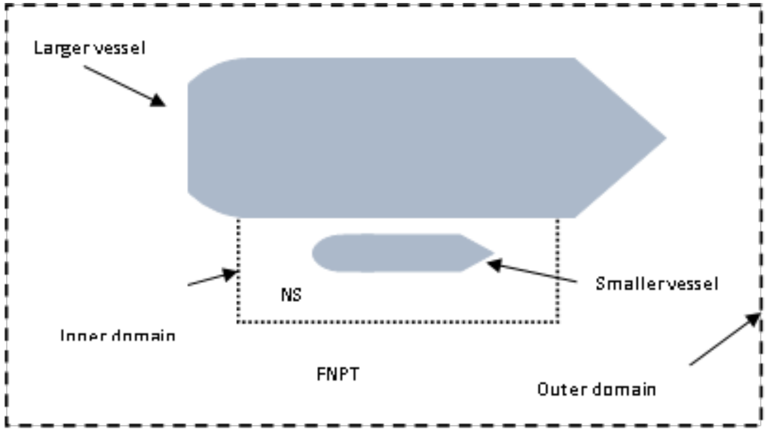
A Zonal CFD Approach for Fully Nonlinear Simulations of Two Vessels in Launch and Recovery Operations (EP/N008847/1)

CODE

- Foam-extend-3.1/extend-bazaar
- Elastic body deformation in two-phase solver

CASES

- Interaction between multiple fluid flows with free surface



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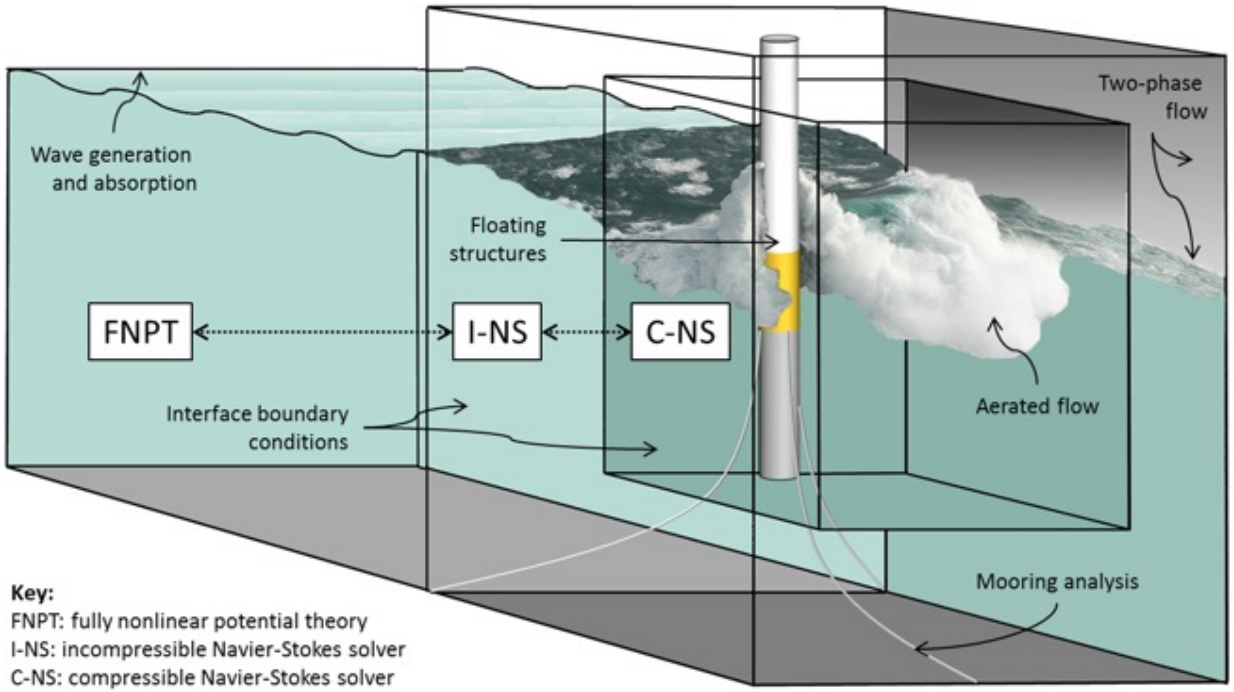
Zonal CFD concept

- For a computationally efficient numerical wave tank (NWT)
- wsiFoam: A multi-region coupling scheme for compressible and incompressible flow solvers for two-phase flow in a numerical wave tank (Martínez Ferrer et al., 2016)



P. J. Martínez Ferrer, D. M. Causon, L. Qian, C. G. Mingham and Z. H. Ma. A multi-region coupling scheme for compressible and incompressible flow solvers for two-phase flow in a numerical wave tank. Computer & Fluids 125, 116–129 (2016). DOI:10.1016/j.compfluid.2015.11.005

OpenFOAM Optimizations for HPC Platform

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Profiling results on ARCHER2: 52M cells

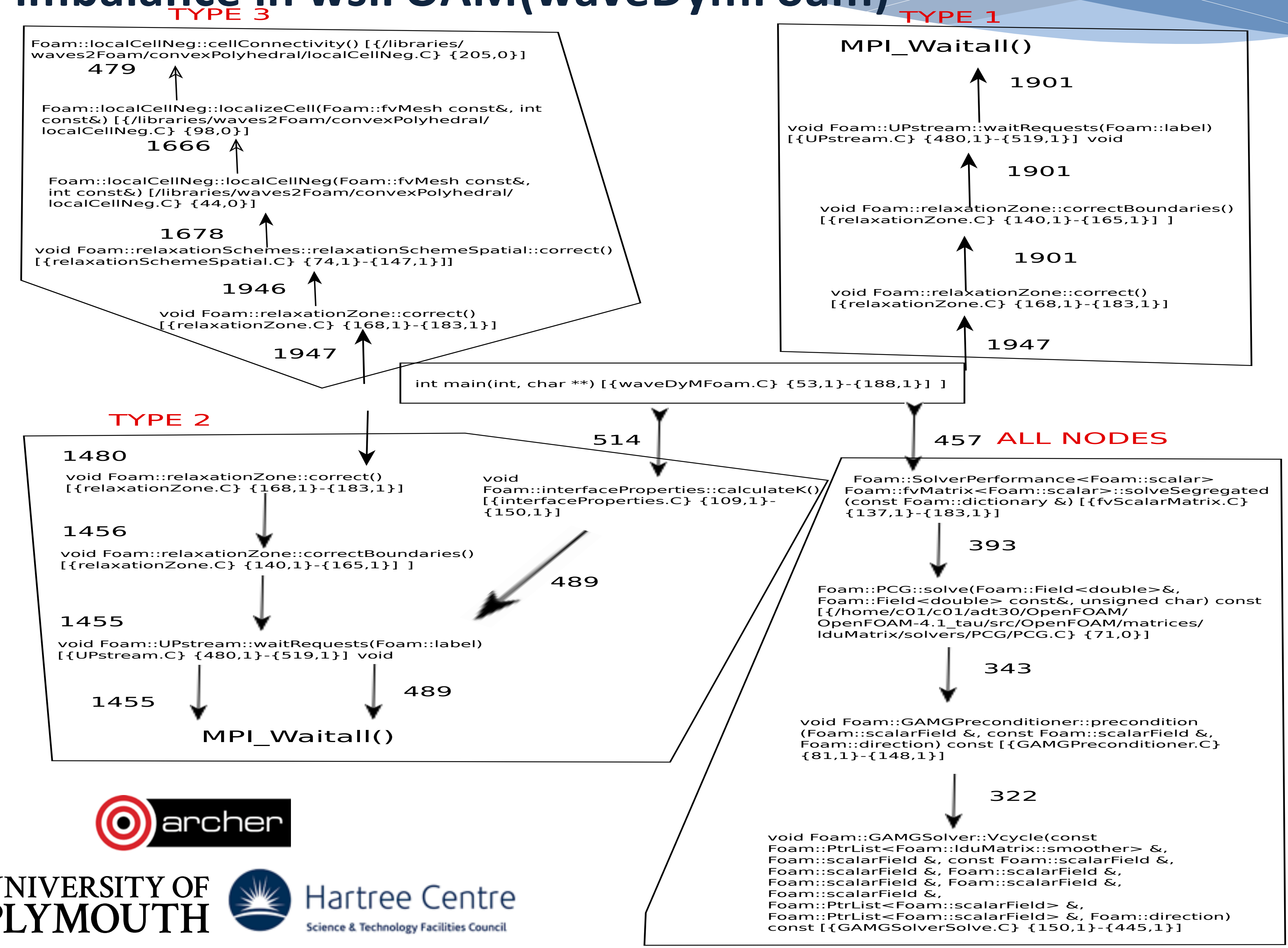
perfdata — vi patreport_openfoam.out — 107x44

Samp%	Samp	Imb. Samp	Imb. Samp%	Group / Function / PE=HIDE
100.0%	99,924.4	--	--	Total
90.0%	89,906.5	--	--	USER
7.8%	7,752.3	1,008.7	11.5%	Foam::surfaceInterpolationScheme<>::dotInterpolate<>
7.5%	7,468.1	1,947.9	20.7%	Foam::DICSmoother::smooth
6.5%	6,519.2	546.8	7.7%	Foam::List<>::List
5.2%	5,231.2	572.8	9.9%	Foam::multiply
4.7%	4,714.9	1,182.1	20.1%	Foam::lduMatrix::residual
3.6%	3,632.9	1,090.1	23.1%	Foam::MULES::limit<>
3.5%	3,466.7	412.3	10.6%	Foam::multiply<>
3.1%	3,070.3	662.7	17.8%	Foam::lduMatrix::Amul
2.4%	2,408.2	897.8	27.2%	Foam::inv
2.4%	2,349.9	558.1	19.2%	Foam::fv::gaussGrad<>::gradf
2.3%	2,277.9	341.1	13.0%	Foam::divide<>
2.2%	2,202.7	286.3	11.5%	Foam::mag<>
1.8%	1,847.1	589.9	24.2%	Foam::outer<>
1.8%	1,765.4	349.6	16.5%	Foam::List<>::operator=
1.6%	1,565.2	628.8	28.7%	Foam::fvc::surfaceSum<>
1.5%	1,527.5	305.5	16.7%	Foam::fvc::surfaceIntegrate<>
1.4%	1,432.4	501.6	26.0%	Foam::GAMGSolver::scale
1.4%	1,372.5	214.5	13.5%	Foam::operator-<>
1.3%	1,326.5	164.5	11.0%	Foam::operator*<>
1.3%	1,275.0	1,052.0	45.3%	Foam::boundBox::boundBox
1.2%	1,181.3	276.7	19.0%	Foam::add<>
1.1%	1,089.8	257.2	19.1%	Foam::fvMatrix<>::H
1.0%	1,022.1	176.9	14.8%	Foam::subtract
1.0%	990.6	244.4	19.8%	Foam::dot<>
1.0%	976.3	125.7	11.4%	Foam::divide
6.8%	6,761.8	--	--	ETC
2.4%	2,364.2	331.8	12.3%	__memset_avx2_unaligned_erms
3.0%	2,965.6	--	--	RT
3.0%	2,958.4	127.6	4.1%	munmap

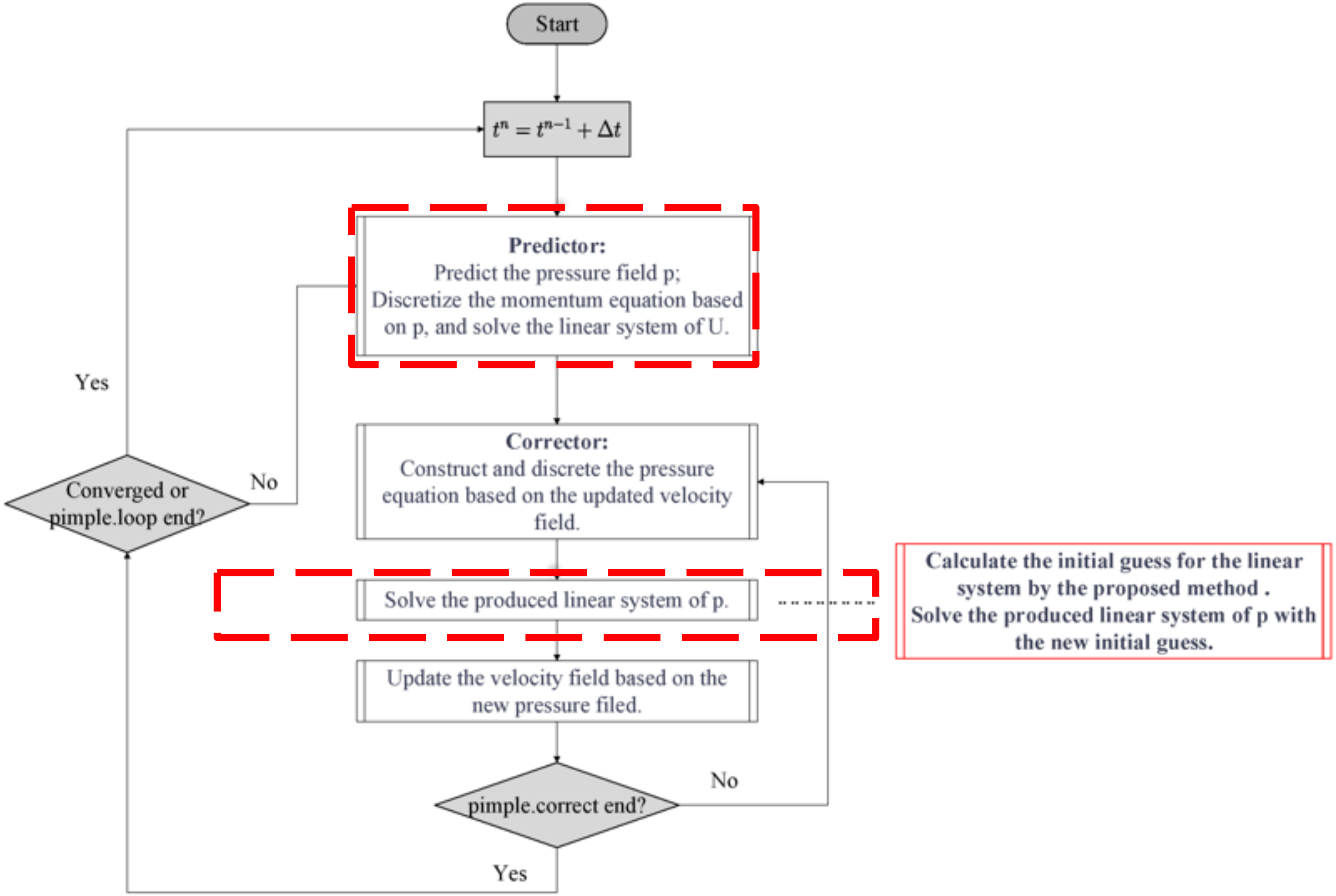
32,0-1 2%

75.5% in linear solver

Load imbalance in wsiFOAM(waveDymFoam)



interFoam solving diagram



HPC Challenges so far

- Complex wave generations with dynamic meshes and large domains
- Code coupling in large scale for both fluid and computational mechanic solvers.
- Overset technologies
- Load imbalance for dynamic meshes
- Sparse linear solvers.
- Heterogeneous computing architectures.

eCSE1208 Project:
Developing a dynamic load balancing library for wsiFoam

Aims and Objectives

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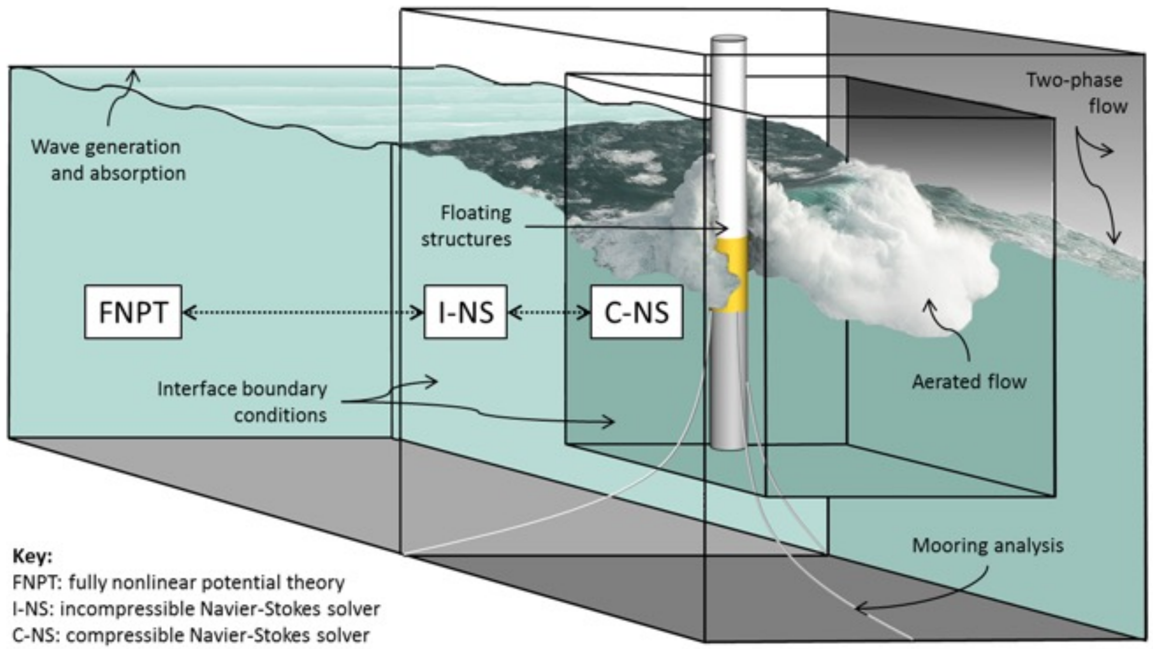
Aim: Develop a dynamic load library compatible with wsiFoam

- **Port wsiFoam code to recent version of OpenFOAM**
- **Introduce new dynamic load balancing functionality**
- **Benchmark performance**



Key:
FNPT: fully nonlinear potential theory
I-NS: incompressible Navier-Stokes solver
C-NS: compressible Navier-Stokes solver

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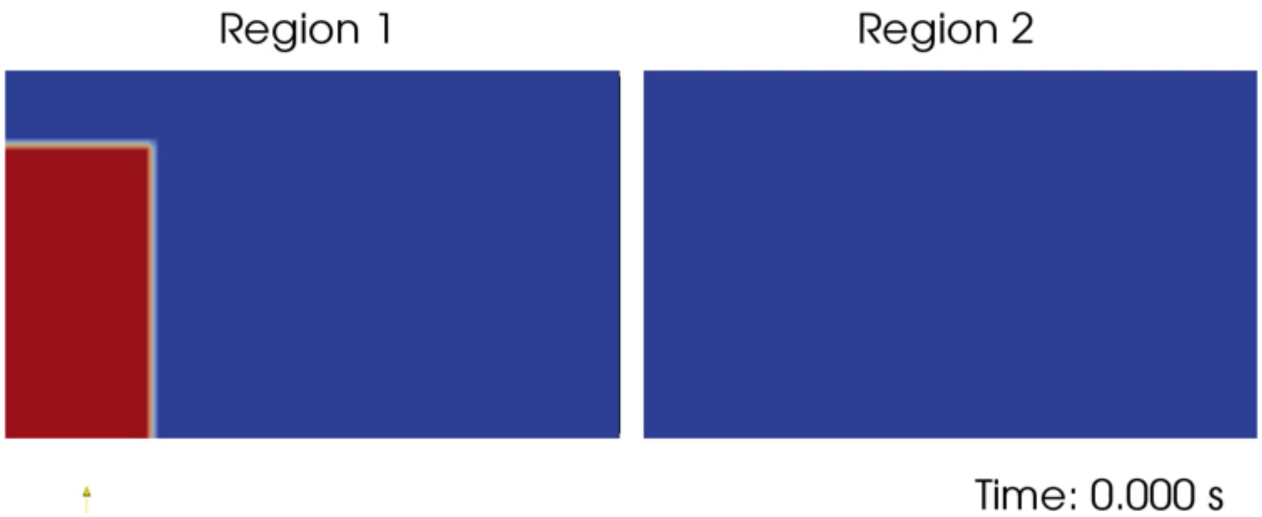
Porting and verification of wsiFoam

Porting

- Original code developed for OpenFOAM 2.3.1
- Code updated for OpenFOAM 5.0
  - New IO functionality
  - Updated VOF schemes
- Extended for be compatibility with waves2Foam for wave generation

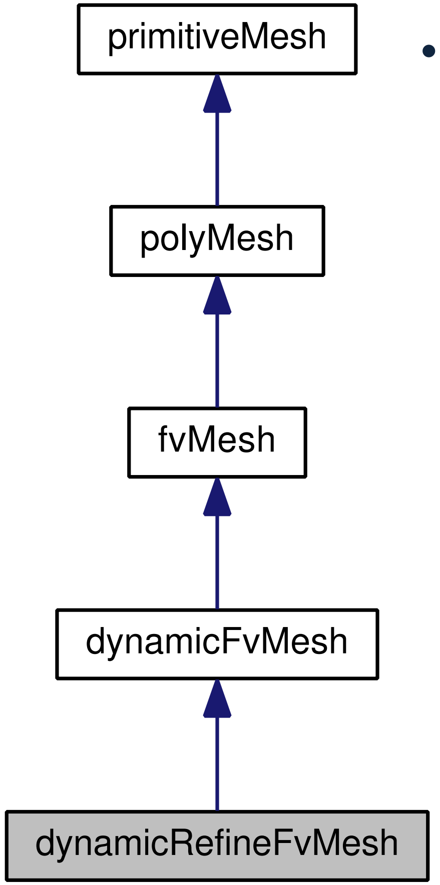
Verification Cases

- Dam break with incompressible and compressible, two-phase solvers
- Floating buoy in focused waves



Jacobsen, N.G., Fuhrman, D.R. and Fredsøe, J. (2012) A wave generation toolbox for the open-source CFD library: OpenFoam, *International Journal for Numerical Methods in Fluids*, vol. 70, pp. 1073--1088

OpenFOAM mesh classes



- **primitiveMesh: mesh base class**
  - **Permanent mesh data**
  - **Geometric data:**
    - **functions to calculate cell centres, cell volumes, face centres, face areas**
  - **Connectivity structure: virtual functions**
    - **points(): point to cells, edges**
    - **Faces():**
    - **faceOwner():**
    - **faceNeighbour():**

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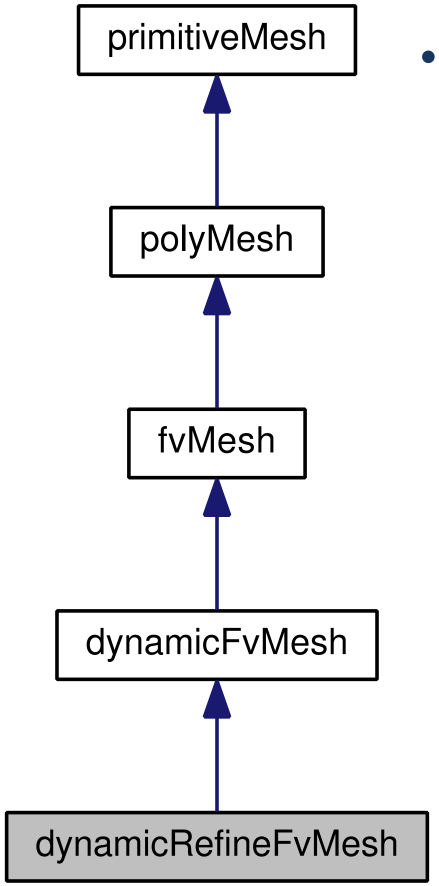
OpenFOAM runtime selection mechanism

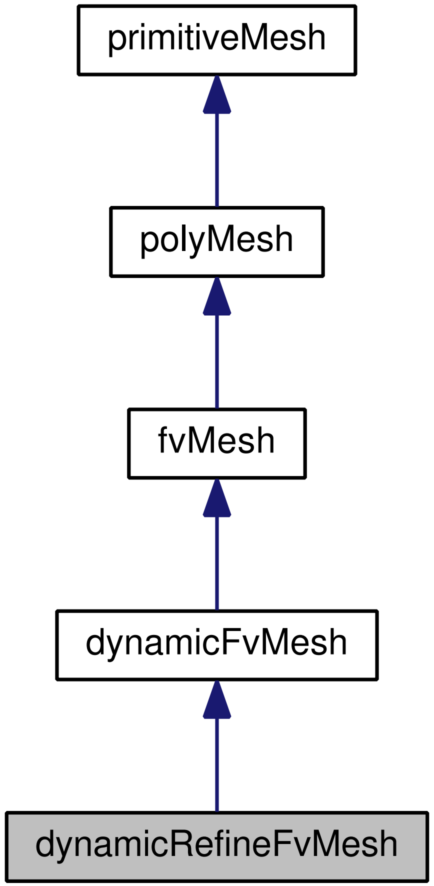
- ”virtual constructor”:
  - not allowed in c++ because build an object the constructor must be of the same type as object.
- Factory method of initialisation
  - A solver interface with generic boundary condition class(base class)
  - You need special boundary condition (derived class)
    - Runtime selection works by creating a hash table of Derived constructor pointers in Base
      - Create a hash table in Base that contains constructor pointers indexed by typeName
      - Have all the Derived add themselves to the list
      - Create a "selector" function in Base called New that

OpenFOAM mesh classes



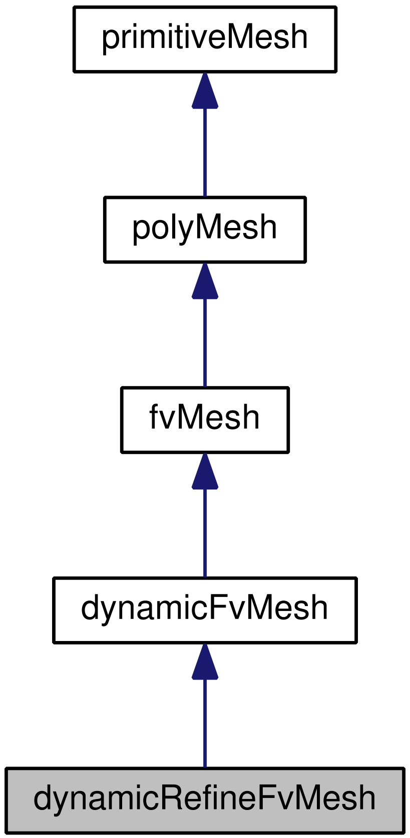
- polyMesh: polyhedral mesh class
  - Inherit primitiveMesh
  - virtual constructor functions
    - points(): point to cells, edges
    - Faces()
    - faceOwner()
    - faceNeighbour()
  - read mesh from file, real mesh container

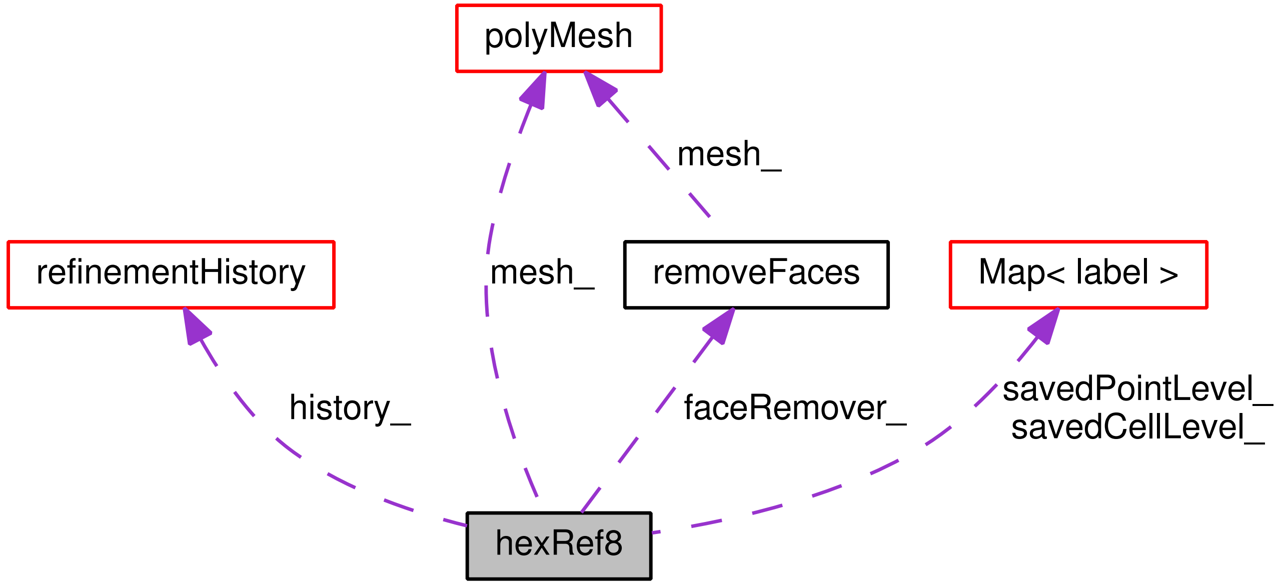
OpenFOAM mesh classes

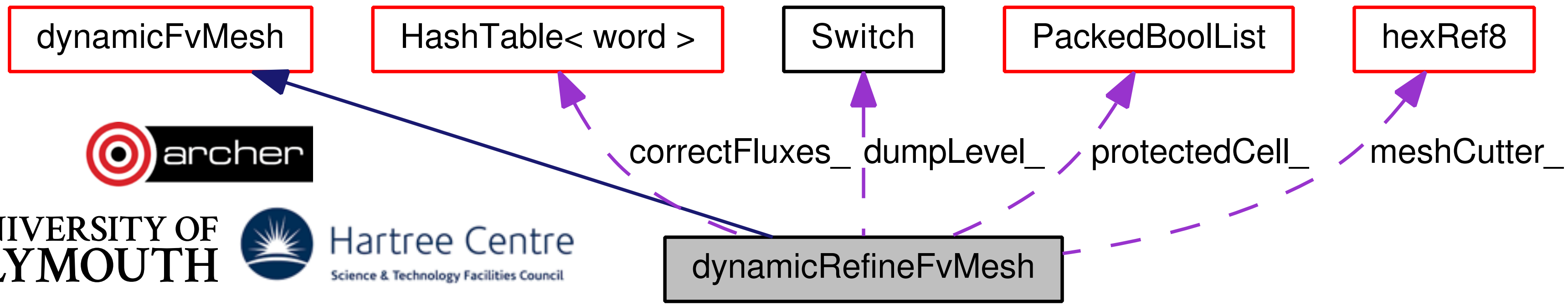


- **fvMesh: finite volume method class**
  - **Functions to do FV discretization**
    - **Face area motion fluxes**
    - **Face area vectors**
    - **Face area magnitudes**
- **dynamcFvMesh: dynamic Mesh base class**
  - **Constructor/deconstructor**
  - **update(): virtual function for mesh update**

OpenFOAM classes for mesh refinement







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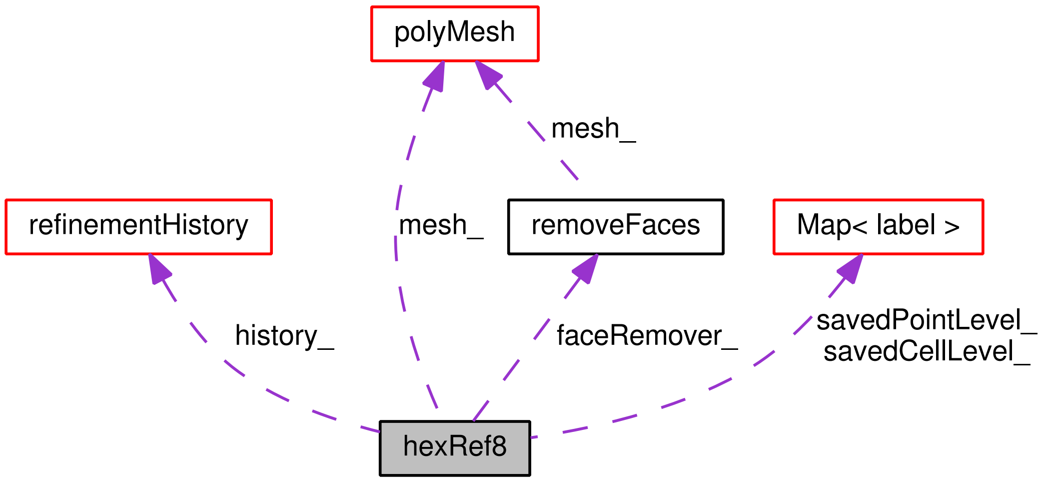
Hexahedral Refinement

- **hexRef8: splitting hexahedral cells into eight subcells**
  - **meshCutter**
  - **polyTopoChange:**
    - **adding()**
    - **removing()**
    - **modifying()**
  - **setRefinement()**
  - **History_: refinement-tree for the mesh**



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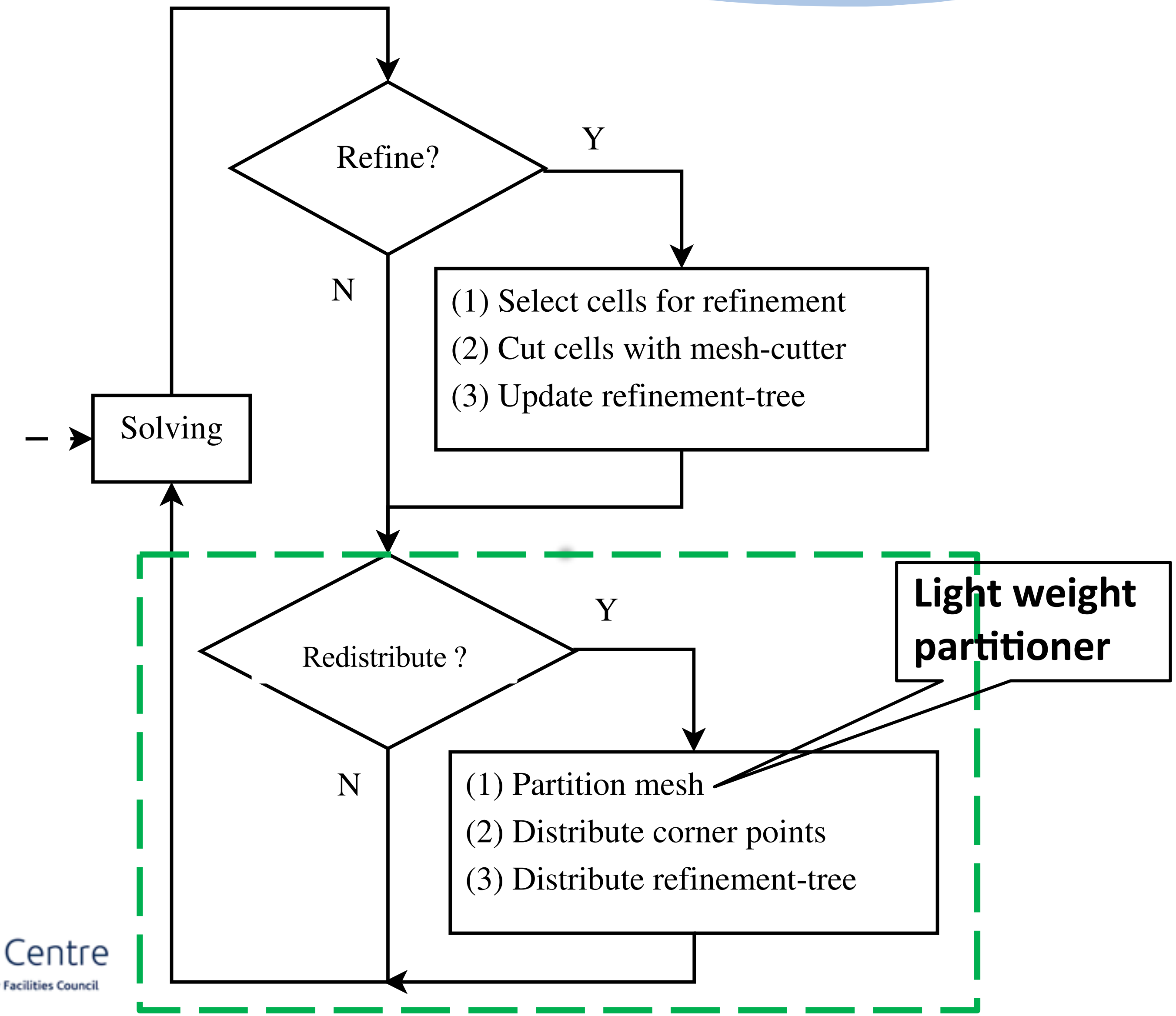
dynamicRefineFvMesh class



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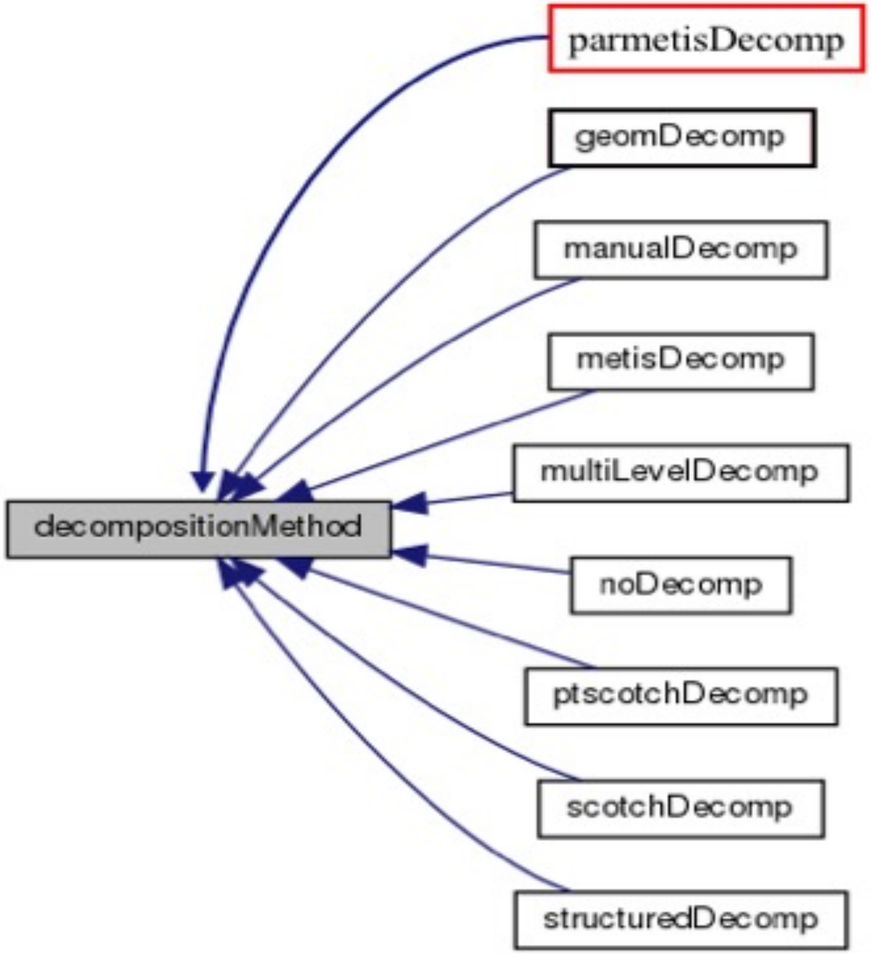
Task 1: Lightweight new decomposition class: parmetisDecomp



Dynamic load imbalance algorithm

Algorithm 1: Dynamic Load Balance Algorithm for DynamicRefineFvMesh

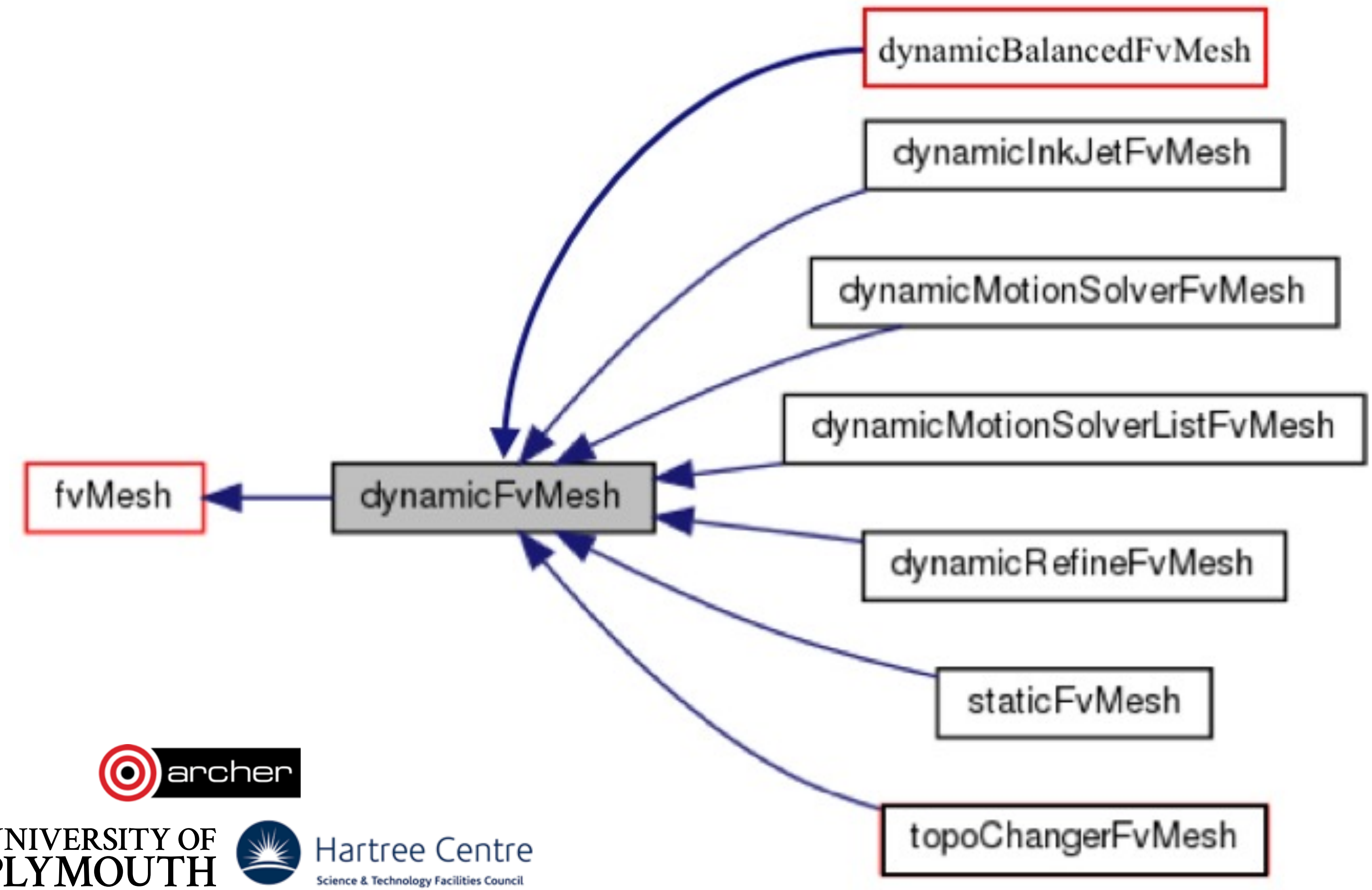
Step 1: Update refinement fields within each MPI partition.
Step 2: Check present level of imbalance with equation (1)
if $maxImb > imbTol$ **then**
  construct the level 0 graph nodes
  calculate each nodes weight with equation (2)
  call repartition with `ParMETIS`
  redistribute the mesh and variable fields
  correct boundary conditions for all fields
end if

Constrain by Refinement History

$$maxImb = max\left(\frac{locNumCells - IdealLocNumCells}{IdealLocNumCells} \times 100\%\right)$$

Developing a dynamic load balancing library

Dynamic load balancing mechanism in OpenFOAM



Using DLB library

- **controlDict**
  - **Add**

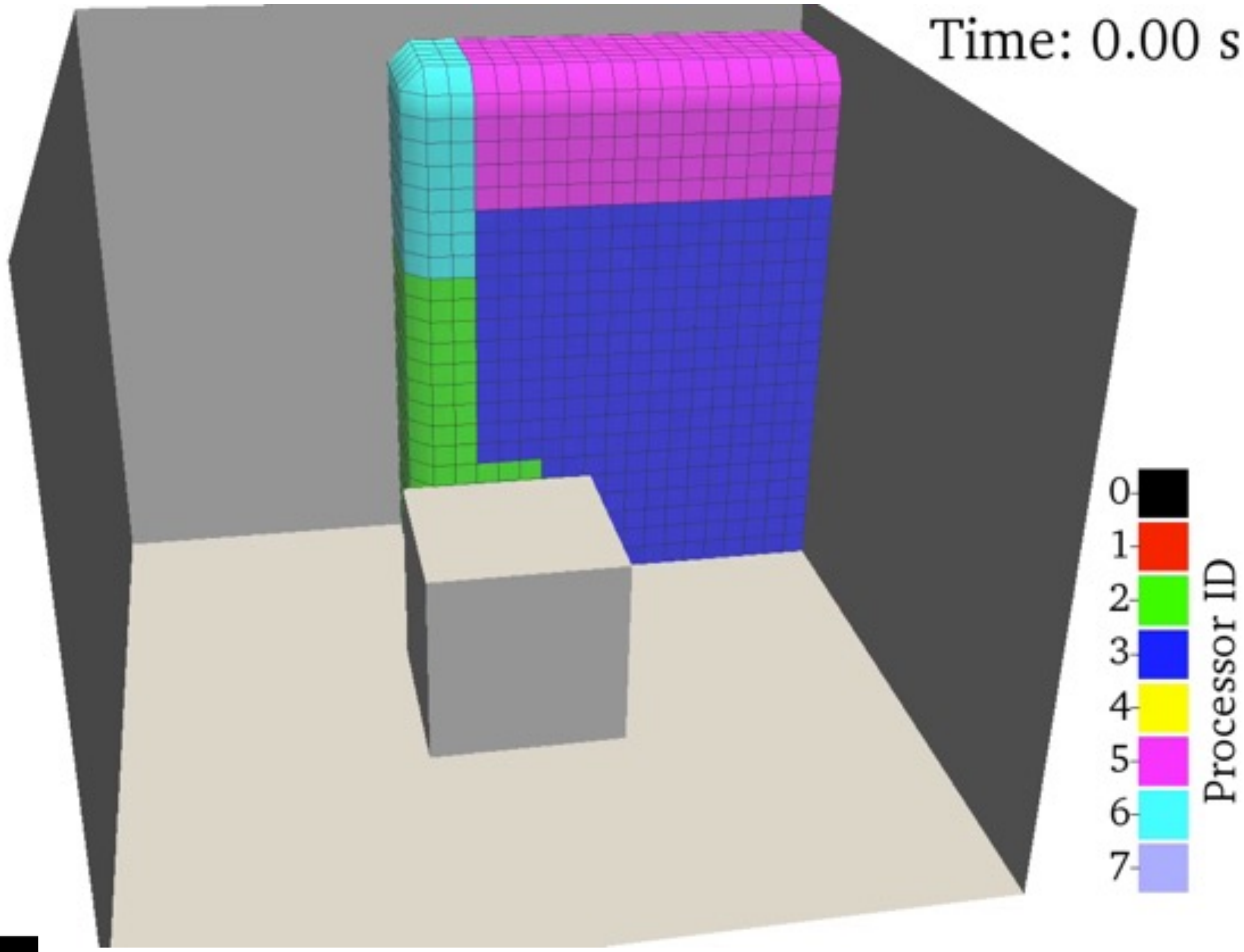
```
libs
(
  "libdynamicBalancedFvMesh.so"
);
```

- **decomposeParDict**

```
method      parmetis;
```

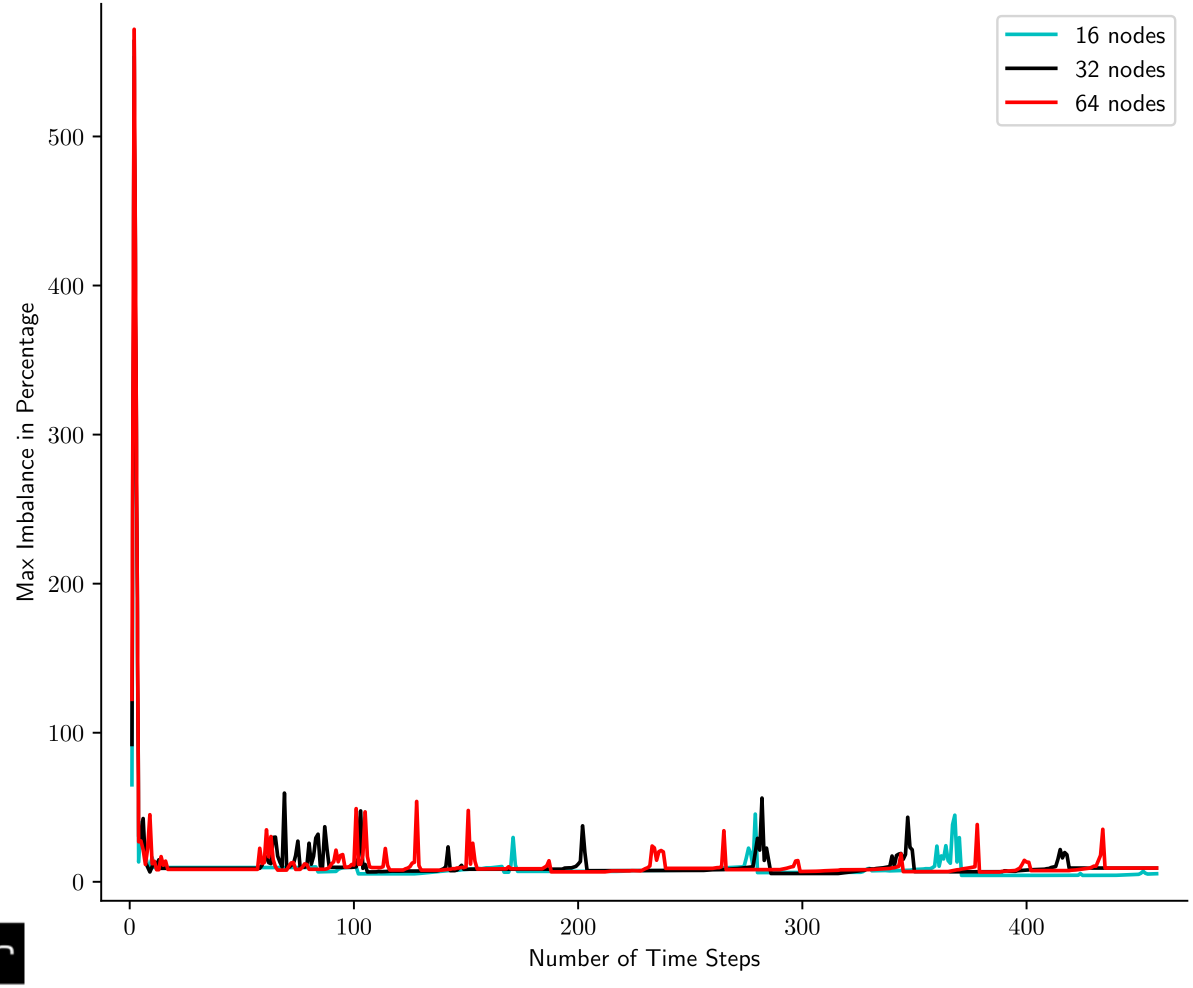
Results and performance analysis

Results and performance analysis

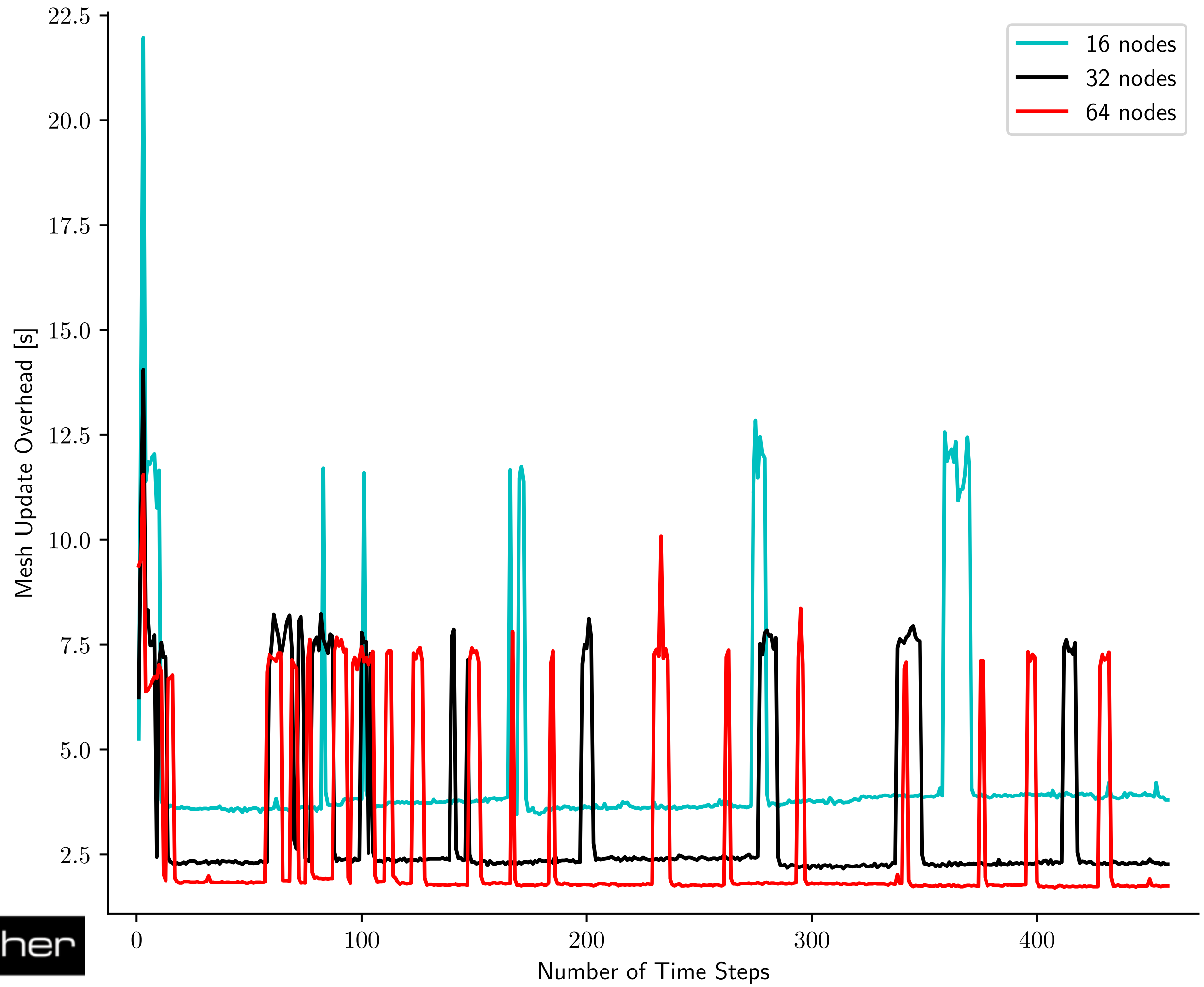


Results and performance analysis

Load imbalance observation

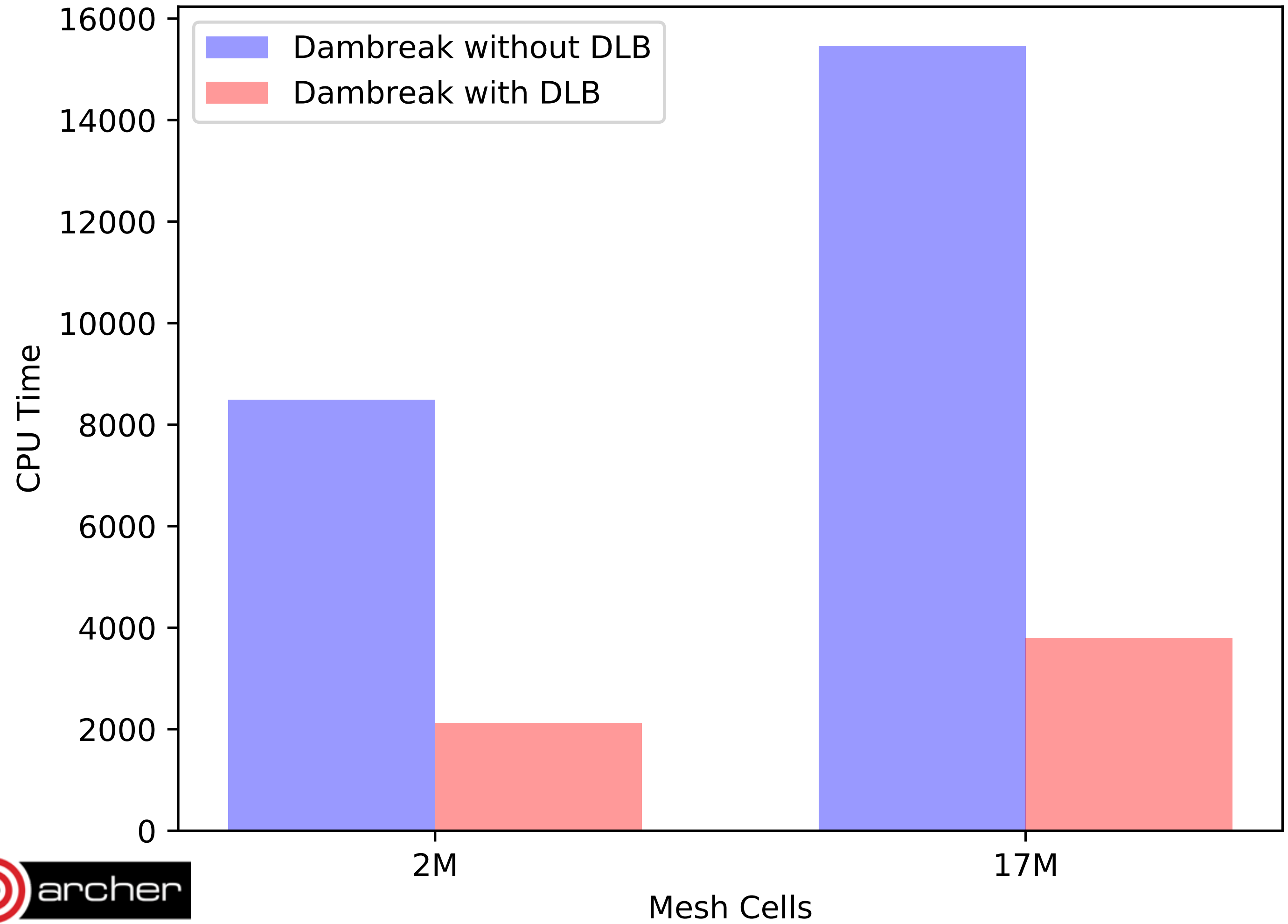


Cost of mesh.update()



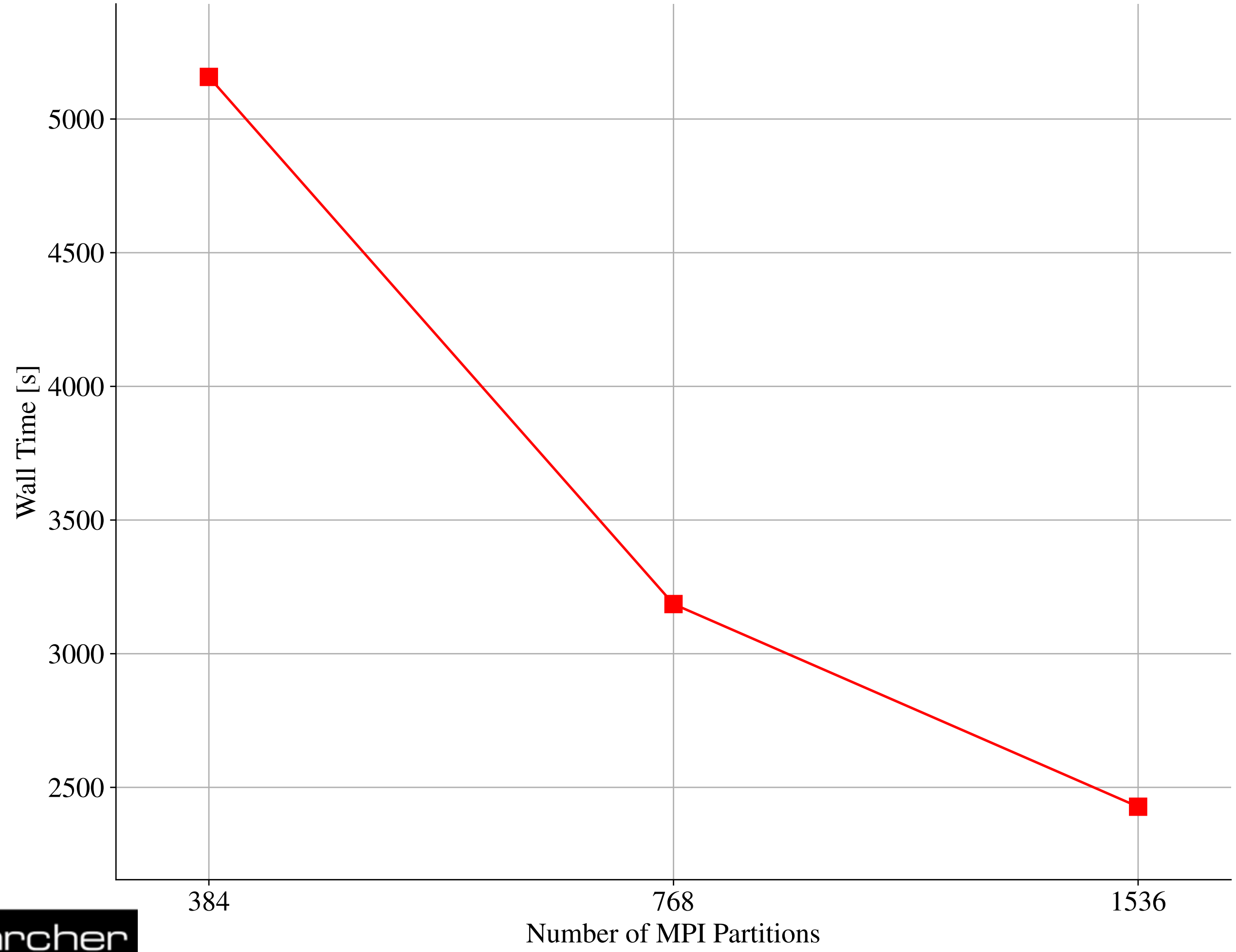
Results and performance analysis

DLB v.s. No DLB



Results and performance analysis

Strong scaling of wsiFoam



Summary and Discussion

- The whole wsiFoam software framework has been successfully ported to OpenFOAM and has been verified using relevant multi-region benchmarks for incompressible and compressible flow.
- A new dynamic load balancing library has been developed
- Presently there are issues when mesh unrefinement is required along with the dynamic load balancing library. Further performance improvement can also be achieved by removing unnecessary I/O (reading dictionaries from files) particularly related to the refinementHistory class implementation.
- A test case using this adaptive mesh functionality was used to benchmark the new library and shows a substantial increase in both the wall time (4-5 times speed up) and the scalability (greater than one thousand cores with more than 50% efficiency) of the wsiFoam solver.

CCP-WSI Code Repository

- Hosted on GitHub
- wsiFoam (OpenFOAM v2206)
    - Dynamic load balancing libraries
    - Test cases

For details on how to get involved and start contributing to the CCP-WSI Code Repository please visit:

https://www.ccp-wsi.ac.uk/code_repository

Acknowledgements

Many thanks to Janis for providing me this opportunity to visit Latvia.

The work was partially funded by the EPSRC Grant ”Extreme Loading on Floating Offshore Wind Turbines (FOWTs) under Complex Environmental Conditions ”. Grant Number:EP/T004339/1. This work has also made use of computational support by CoSeC, the Computational Science Centre for Research Communities, through CCP-WSI+:Collaborative Computational Project on Wave Structure Interaction +

Thanks, Questions ?