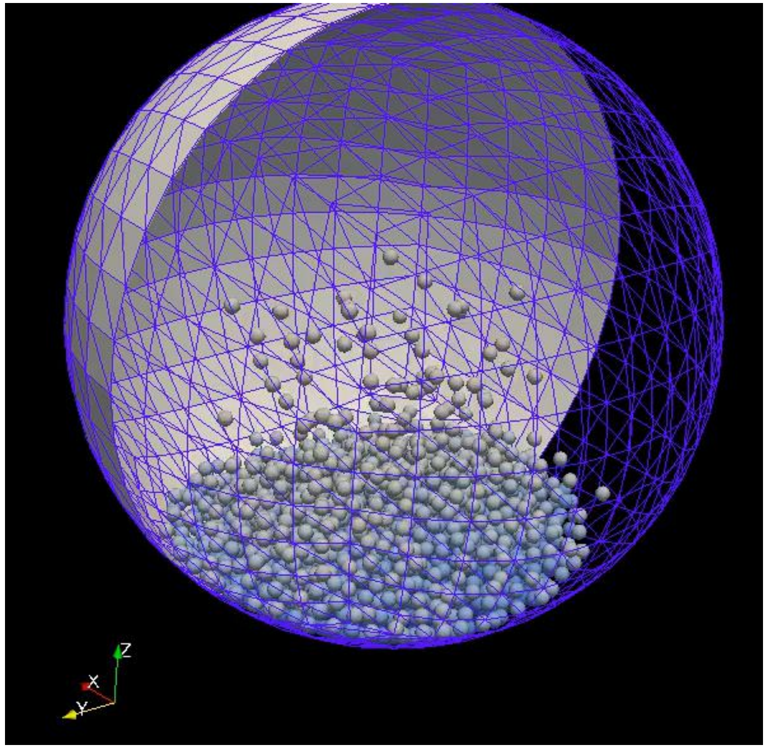
QUEEN'S UNIVERSITY BELFAST

SCHOOL OF MECHANICAL AND AEROSPACE ENGINEERING

OPTIMISATION OF MOTION CONTROL FOR ROTATIONAL MOULDING



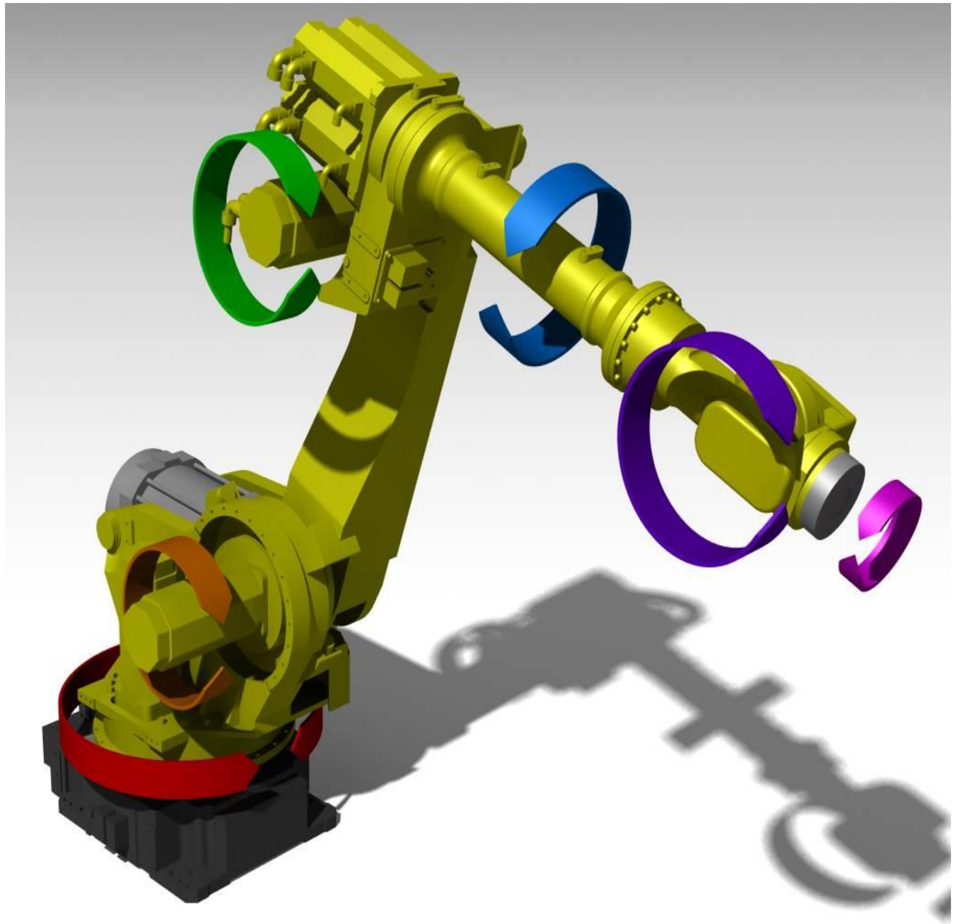
MR. JONATHAN ADAMS[1], DR. YAN JIN[1], DR. DAVID BARNES[2] & DR. JOSEPH BUTTERFIELD[1]

1. SCHOOL OF MECHANICAL & AEROSPACE ENGINEERING
2. SCHOOL OF MATHEMATICS & PHYSICS

21/10/2018

AGENDA

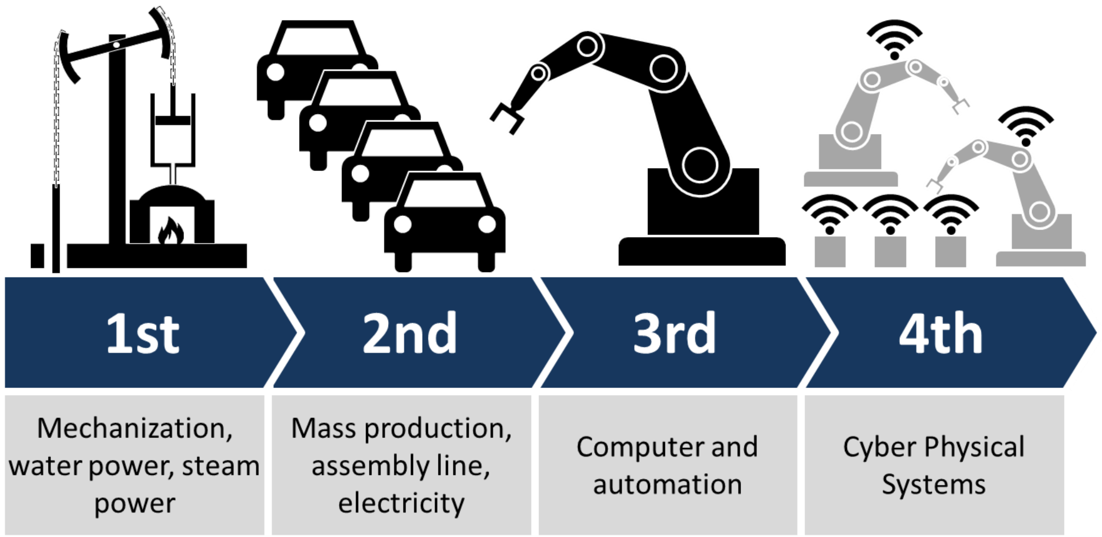
- Introduction & Background
  - Challenge: Industry 4.0
- Simulation:
  - Optimising Rotational Path
  - Optimising Rotational Speed
- Conclusions & Future Work



INTRODUCTION & BACKGROUND

Motivation:

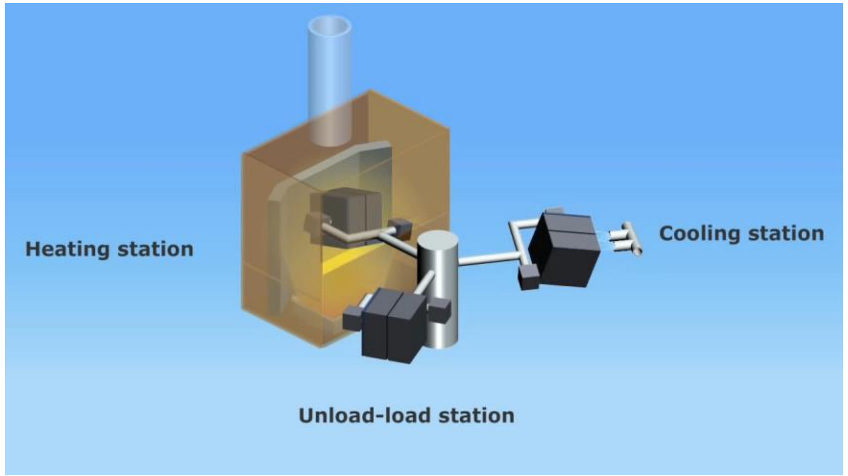
- Robot based rotational moulding **(Industry 4.0)**.
  - Computer based:
    - Planning
    - Execution
    - Control
    - Feedback
  - More flexibility & control of mould rotation.
  - Great potential to improve product quality and cycle time.



Industrial Revolutions

Current Limitations:

- Machinery seen little change over past 60 years – Lack of connectivity.
- Bi-axial machines use constant speeds and speed ratios.
  - Limits control over powder motion and distribution.
  - Restricts wall thickness uniformity.
- Rotational speeds & speed ratios found through trial & error approach.
  - Inefficiencies (time, material, and energy).



Constant speed Bi-axial Rotation

PROBLEM

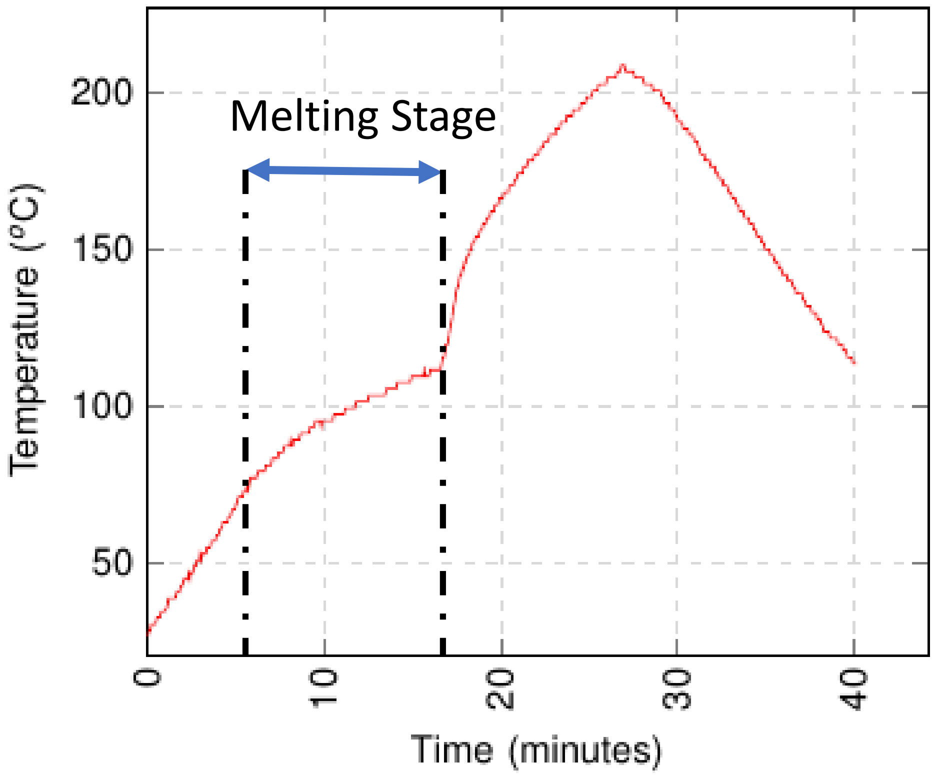
Wall thickness uniformity can be a challenge.

- Common parts made to +/- 20%.
- Nominal wall thickness often used.
- Wasteful (material, manufacturing time, energy).

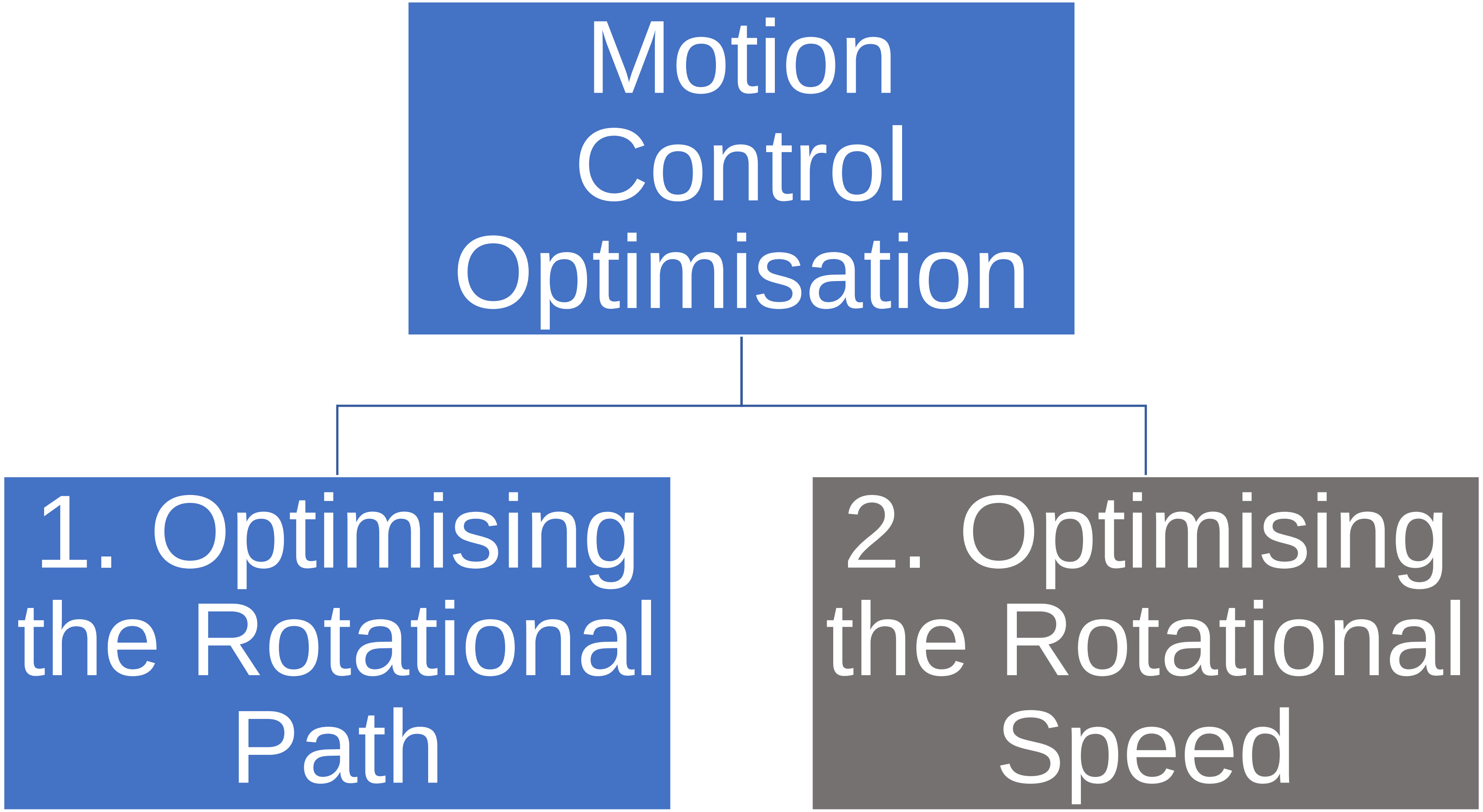
Factors that effect wall thickness uniformity:

- Mould wall thickness variations.
- Powder quality & flowability (shape, density, PSD).
- Mould geometry.
- Heating system.
- **Rotational Path (Currently controlled by speed ratio).**
- **Rotational speed.**

Internal Air Temperature Trace



QUEEN'S UNIVERSITY BELFAST


Motion Control Optimisation
1. Optimising the Rotational Path
2. Optimising the Rotational Speed

1. OPTIMISING ROTATIONAL PATH:

AIM

- Improve the powder-wall contact time (PWCT) uniformity by utilizing increased flexibility and control over the mould rotation that becomes possible with additional axes of rotation.

OBJECTIVES

- Investigate restrictions and limitations with current bi-axial motion control method for spherical mould.
- Describe new rotational paths that uniformly cover the mould surface.
- Validate new rotational paths.
  - Simulate powder flow inside rotating mould.
  - Compare PWCT uniformity.

QUEEN'S UNIVERSITY BELFAST

STATE OF THE ART

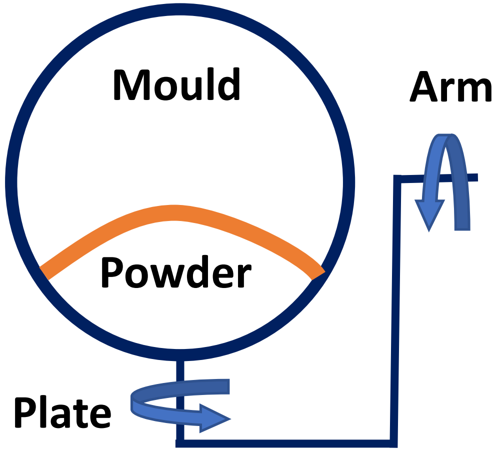
Case Study: Sphere Mould

Current Practice:

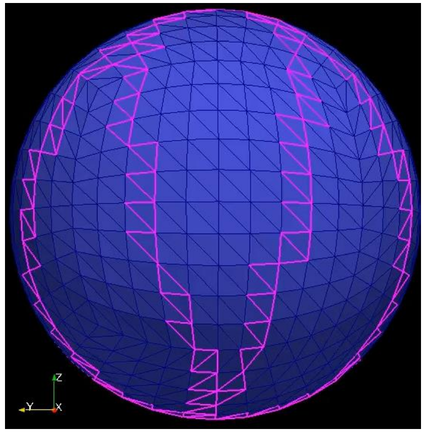
- Biaxial rotation (with constant speeds & ratios).
- 4:1 speed ratio commonly used.
- Powder distribution is controlled by the rotational path of mould.

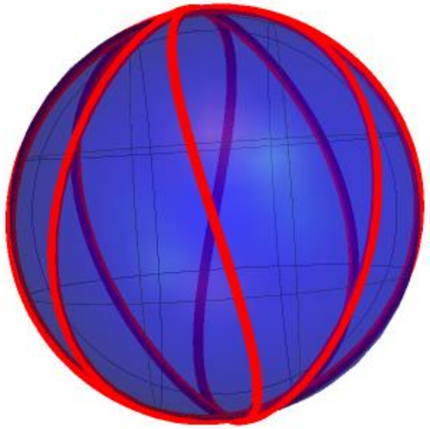
Table 1. Optimum speed ratio for range of mould geometries [1].

Speed Ratio Arm:Plate	Shapes
8:1	Cylinders (horizontally mounted).
4:1	Spheres, cubes.
2:1	Rings, tyres, round flat shapes.
1:5	Cylinders (Vertical mounted).



Arm : Plate





4 : 1 Speed Ratio

Tracing the path on mould surface that travels through bottom point of sphere

Improved flexibility and control of mould rotation now available.
Can this be utilised to allow a better path over the mould surface to be designed?

QUEEN'S UNIVERSITY BELFAST

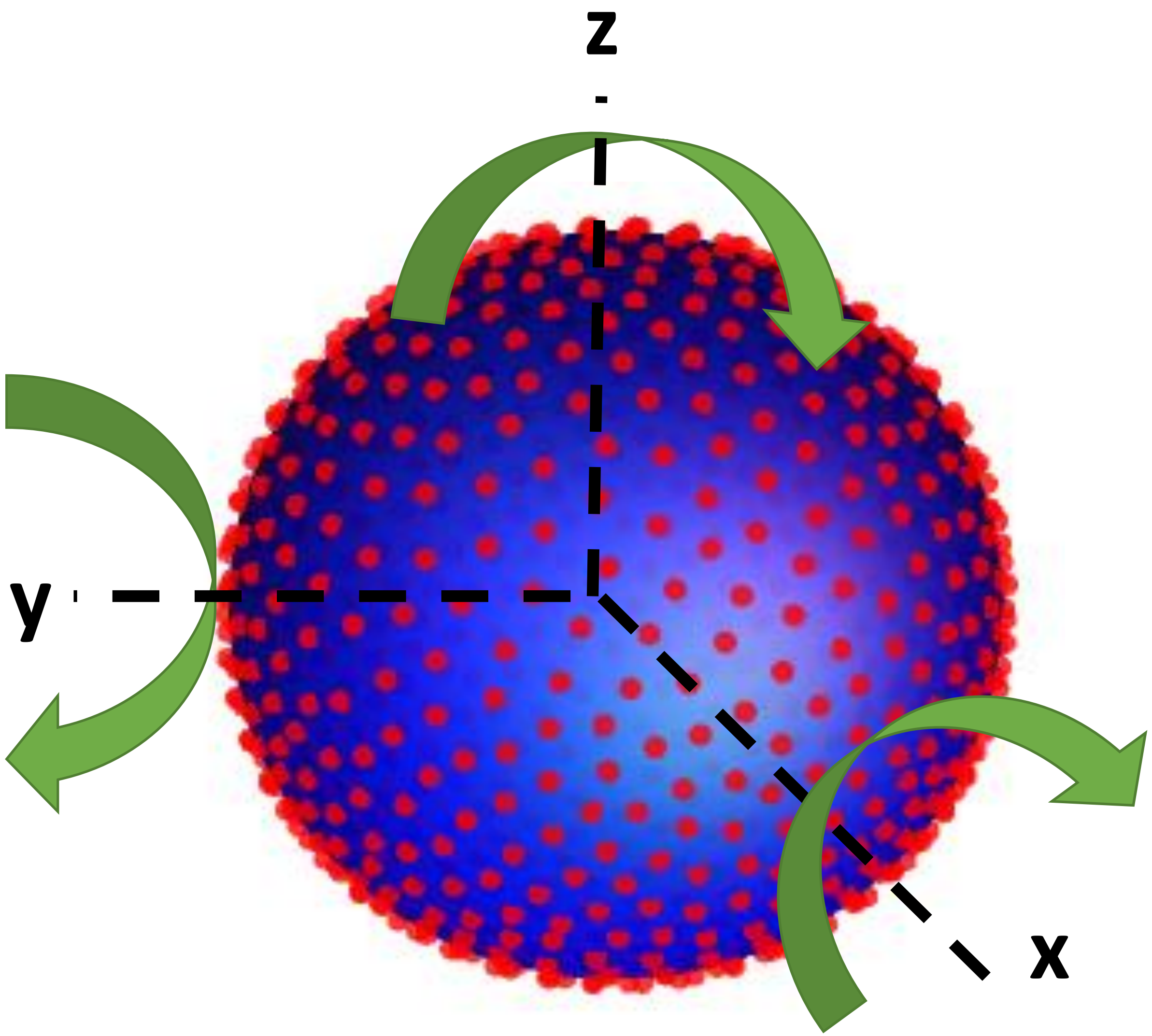
[1] R. J. Crawford and M. Kearns, Practical Guide to Rotational Moulding. iSmithers, Rapra Publishing, 2003.

OPTIMISING ROTATIONAL PATH

With increased control over mould rotation,

What is the optimal way to rotate sphere mould?

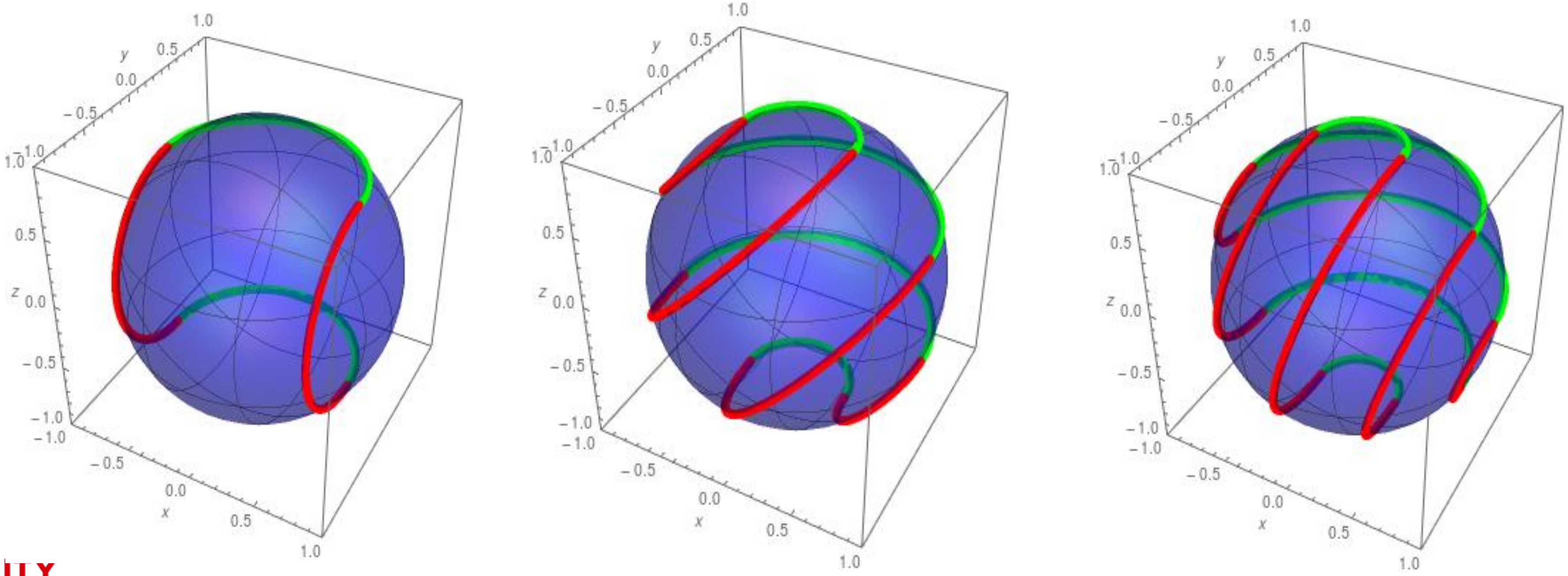
- A rotational path is required that allows each node on sphere surface to spend a more uniform time in contact with powder bed.



QUEEN'S UNIVERSITY BELFAST

OPTIMISING ROTATIONAL PATH – ‘SPHERE FILLING’ CURVE APPROACH

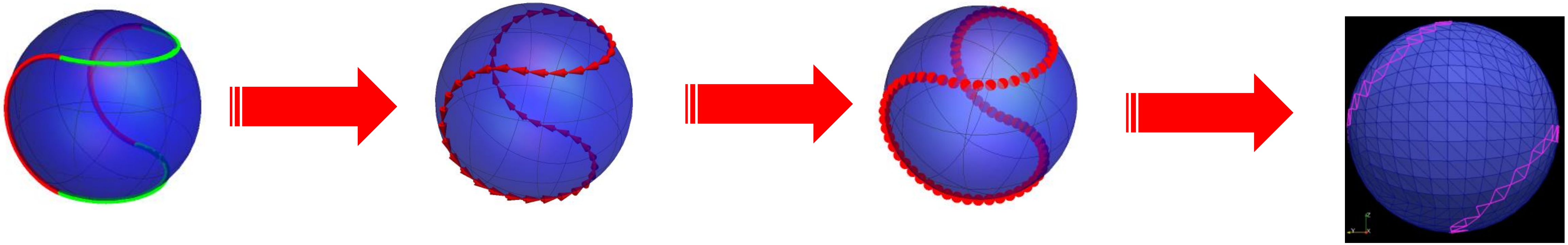
- Mathematic solution of optimum path.
- Evenly covers/inspects all areas of sphere surface.
- Equal amount of ‘traffic’ to all areas.
- Continuous path (closed loop).



Sample ‘Sphere filling’ curves

OPTIMISING ROTATIONAL PATH – ‘SPHERE FILLING’ CURVE APPROACH

Obtaining rotations required to move ‘sphere filling’ curve through powder bed.



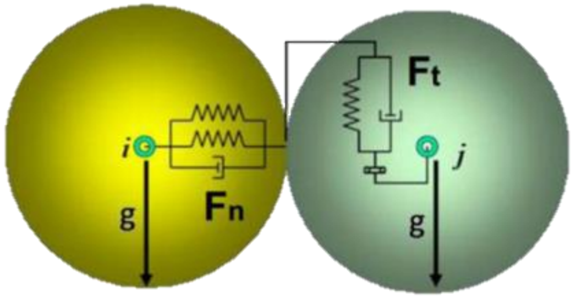
QUEEN’S UNIVERSITY BELFAST

SIMULATING POWDER FLOW - DISCRETE ELEMENT METHOD (DEM)

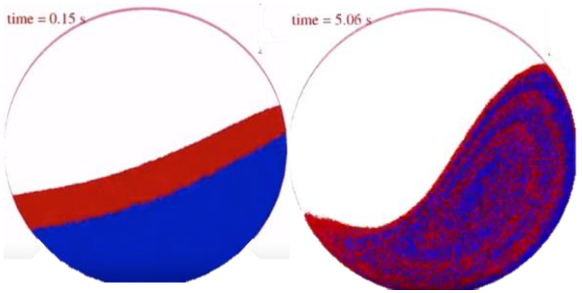
- Mathematical approach to modelling granular/powder flow.

What is Discrete Element Method?

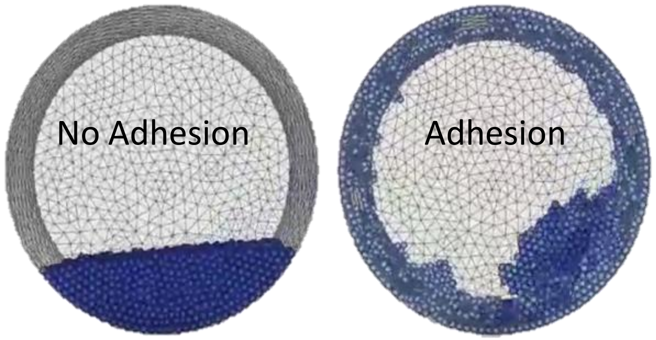
- Shows macroscopic behaviour of powder by modelling the microscopic forces.
- Particle-particle and particle-wall contact forces modelled.
- Forces used to calculate particles motion.
- Capable of modelling many of the variables within rotational moulding (Powder mixing, Particle adhesion, PSD, heat transfer).



DEM particle contact model



DEM simulating powder mixing



DEM modelling powder adhesion

QUEEN'S UNIVERSITY BELFAST

SIMULATION: DISCRETE ELEMENT METHOD (DEM) SETUP

LIGGGHTS®

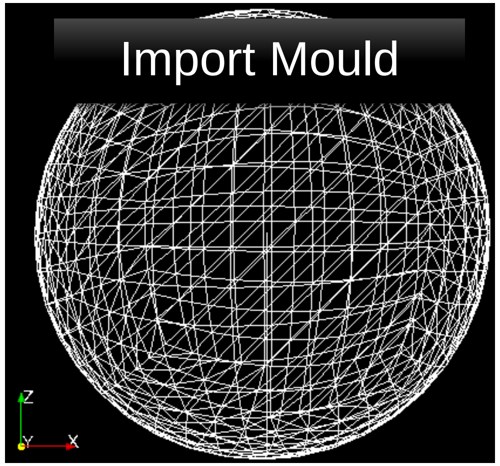
Insert mould geometry.
- Model sphere using CAD.
- Mesh model (STL file).

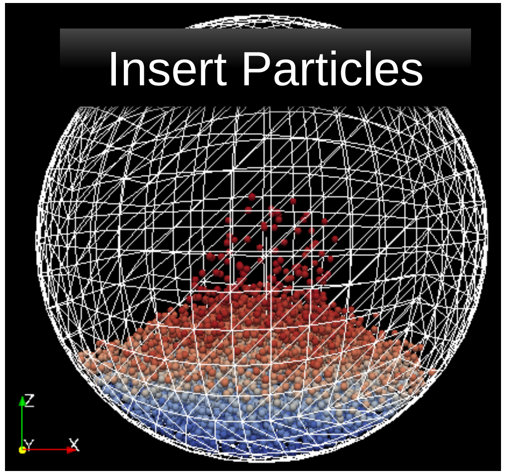
Define particle properties.
- Material: LMDPE
- Density: 0.935 g/cm^3
- Radius: 50-350µm
- Young's Modulus: 700 MPa
- Friction (Particles): 0.25
- Friction (Particle-wall): 0.7
- Restitution coefficient: 0.4

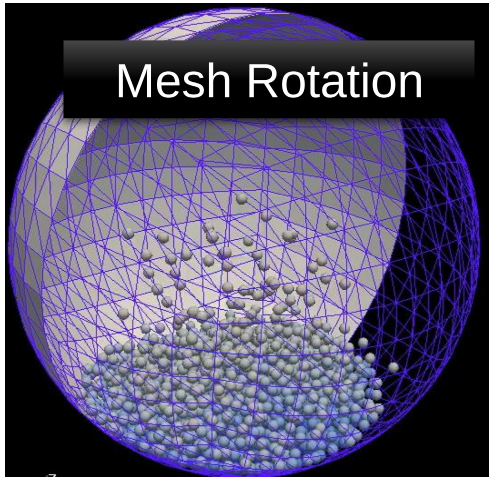
Particle insertion.
- Specify particle insert region.
  - Centre of mould.
  - Fall to bottom under gravity.

Wait
Allow particles to settle

Rotation
- 4:1 speed ratio.
- **'Sphere filling' path**





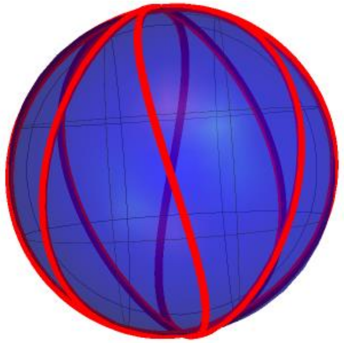
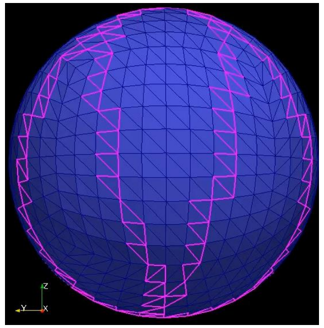
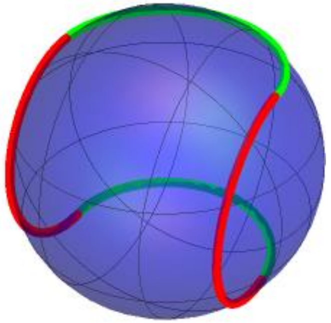
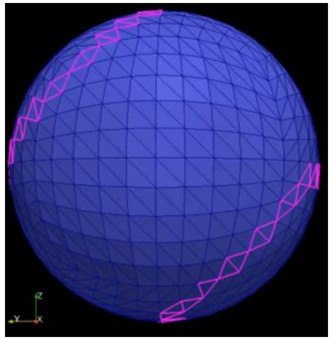
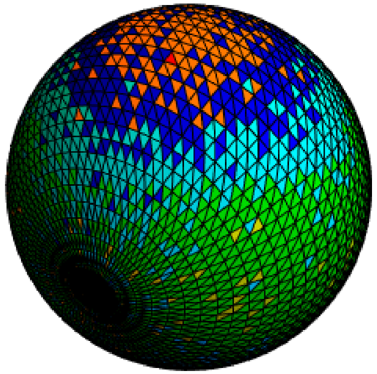
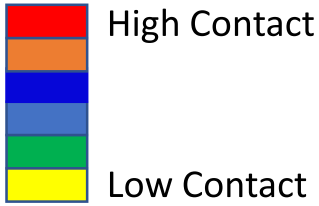
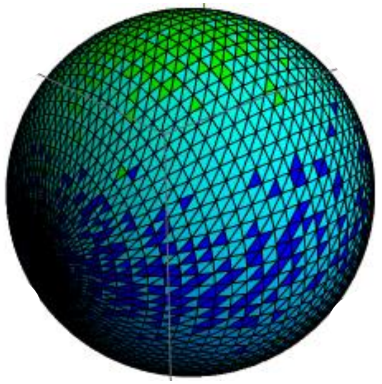


QUEEN'S UNIVERSITY BELFAST

- **Contact between each mesh element and powder monitored during simulation <u>(Used to find powder wall contact time (PWCT) uniformity)</u>.**

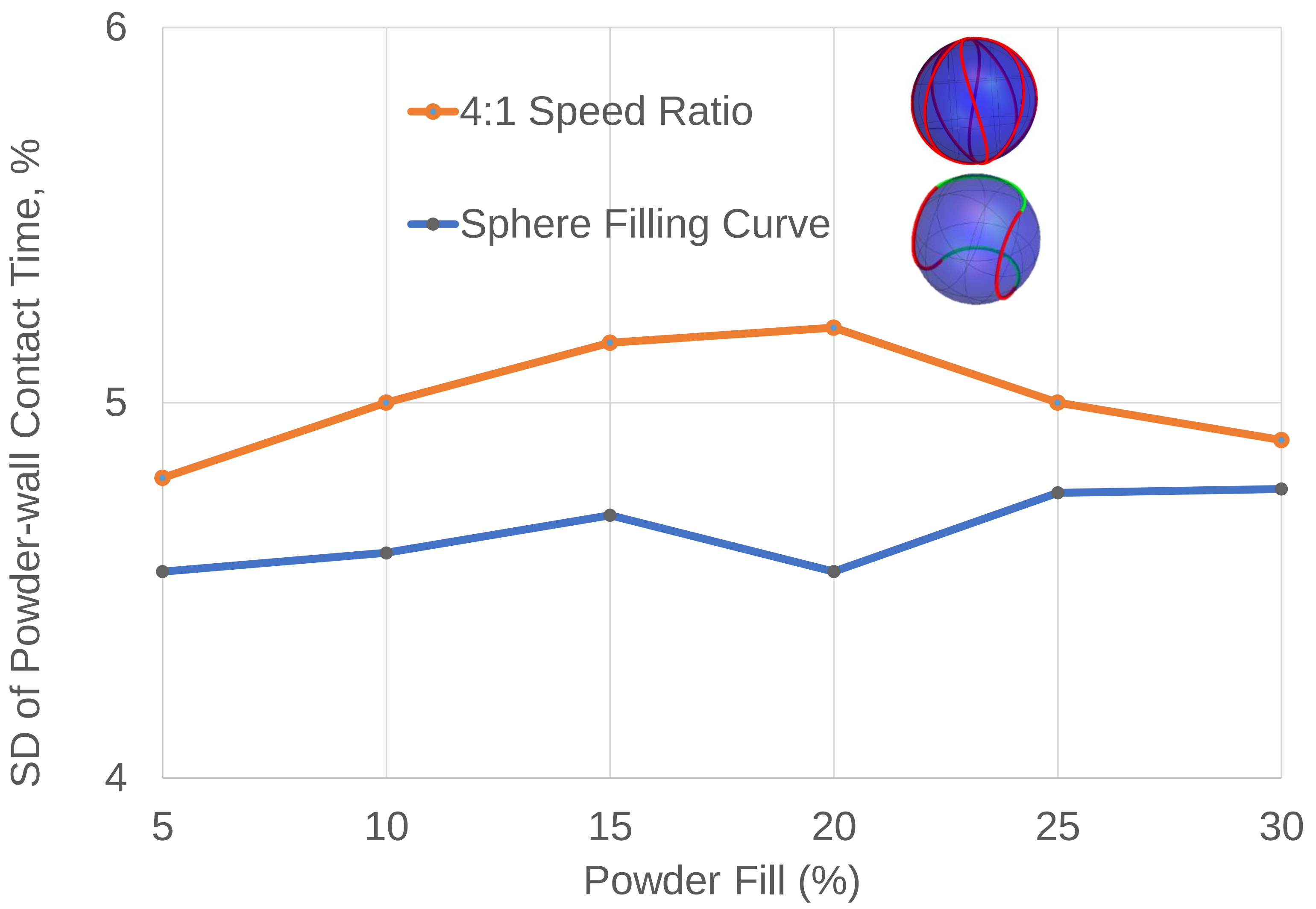
SIMULATION RESULTS

- Results for 20% powder fill

	4:1 Speed Ratio	'Sphere Filling' Curve
Rotational Path	 	 
Plotted Powder-wall Contact Time (PWCT)	 	
Standard Deviation (SD) Contact Time (%)	**5.2**	**4.5**

OPTIMISING ROTATIONAL PATH - SIMULATION RESULTS

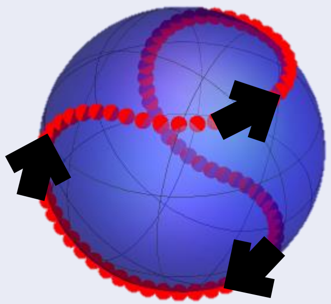
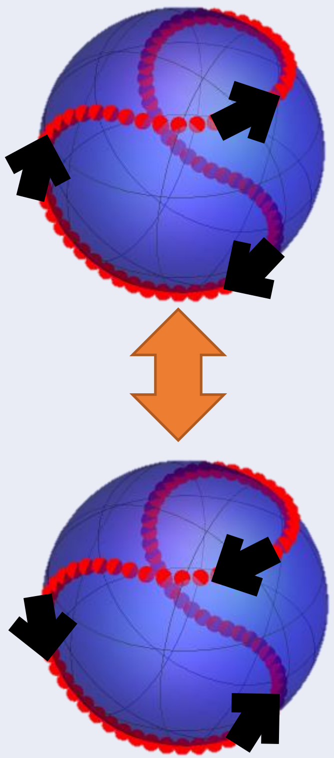
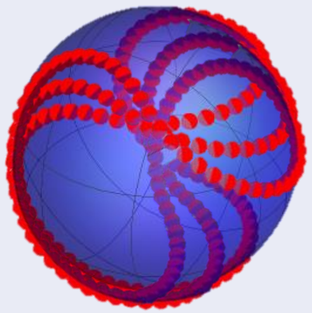
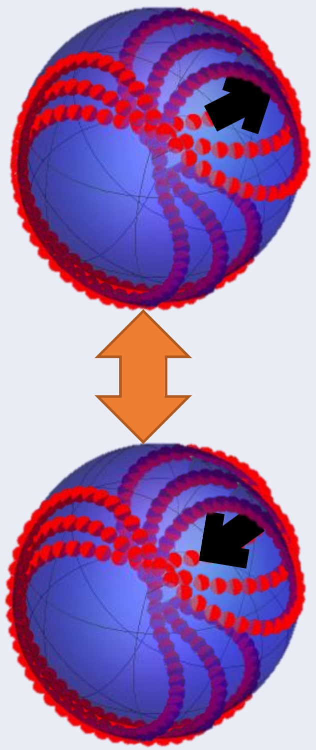
- Results for range of powder fill levels (5-30%).
- Sphere Filling curve rotations found to improve powder distribution by up to 13%.



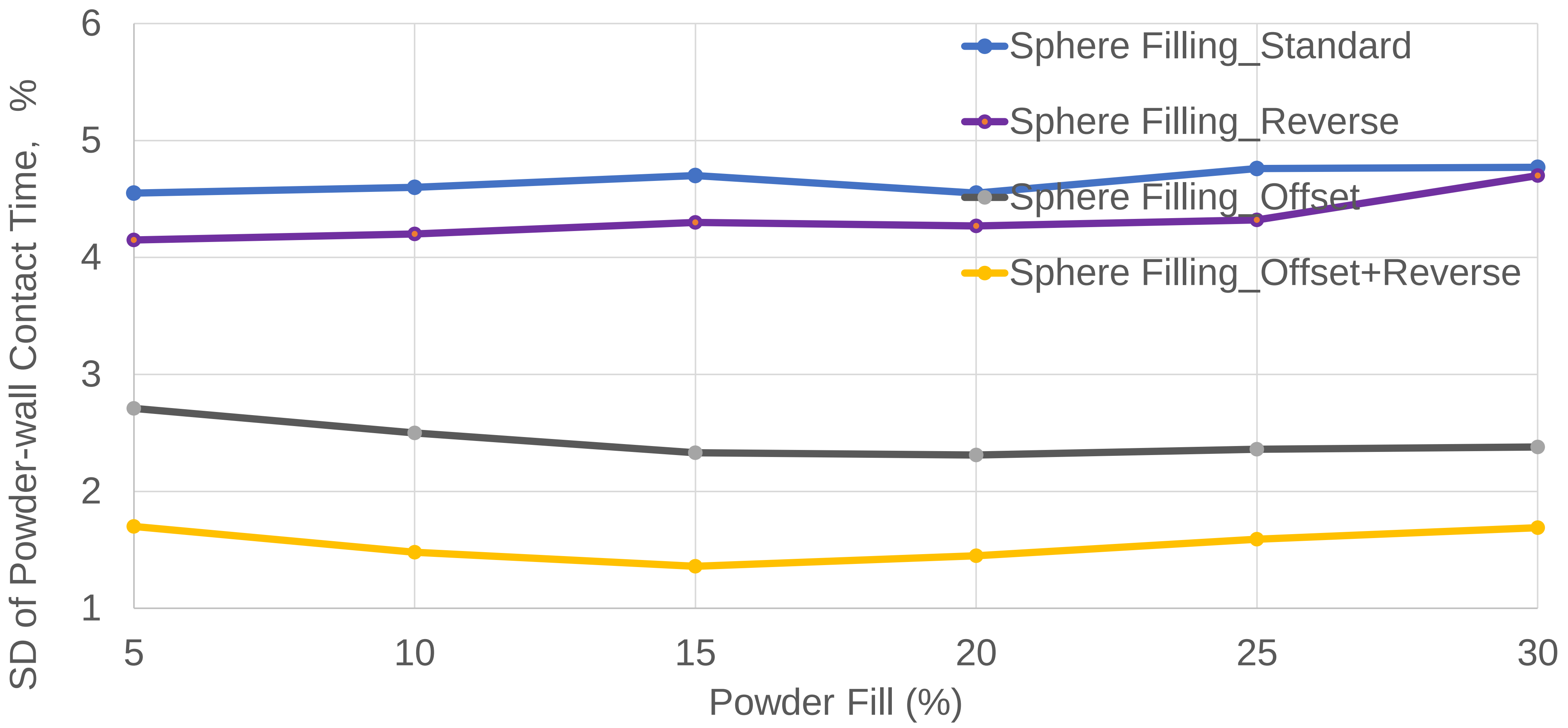
QUEEN'S UNIVERSITY BELFAST

OPTIMISING ROTATIONAL PATH - SIMULATION RESULTS

- Variations of ‘sphere filling’ (SF) curve path investigated with aim to further improve PWCT uniformity.

1. SF curve_standard	2. SF curve_reverse	3. SF curve_offset	4. SF curve_offset+reverse
‘Sphere filling’ curve	‘Sphere filling’ curve - With rotation direction reversed.	‘Sphere filling’ curve - with curve offset after each loop.	‘Sphere filling’ curve - with curve offset after each loop. - with rotation direction reversed.
			

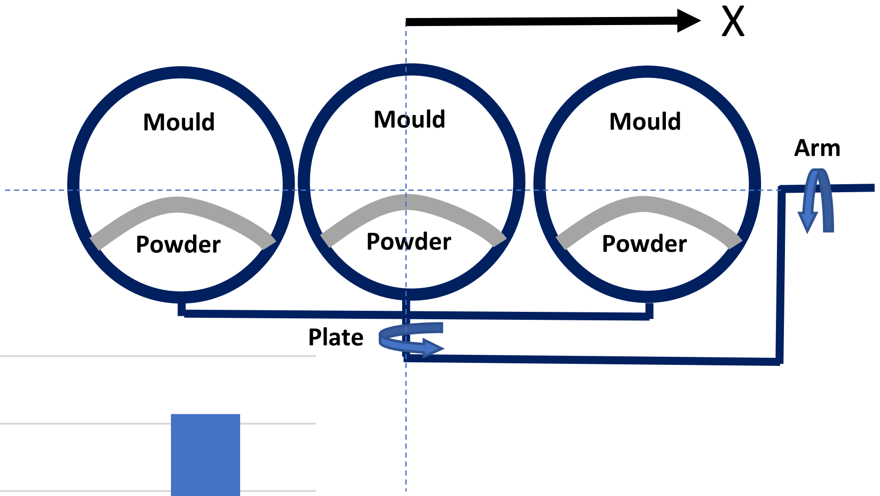
OPTIMISING ROTATIONAL PATH - SIMULATION RESULTS

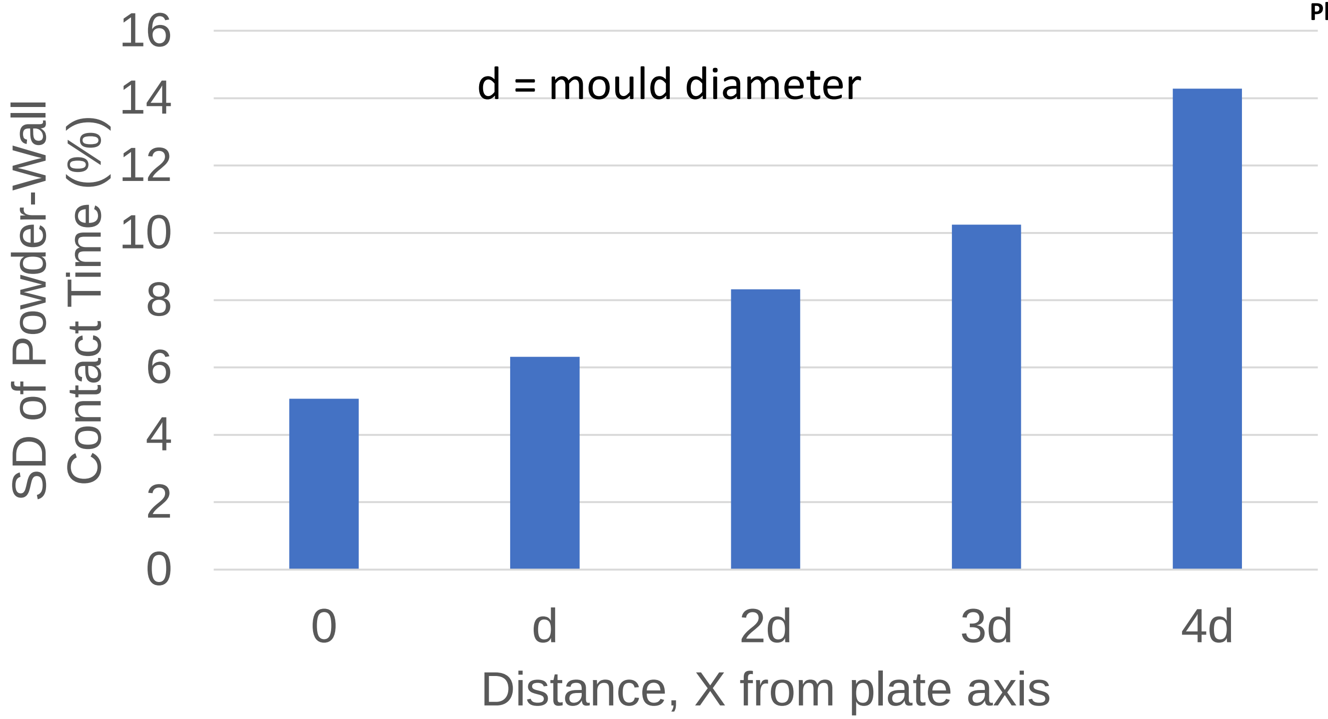


QUEEN'S UNIVERSITY BELFAST

- **Distribution improved by up to 75% compared to 4:1 speed ratio.**

SIMULATION RESULTS - EFFECT OF MOULD POSITION

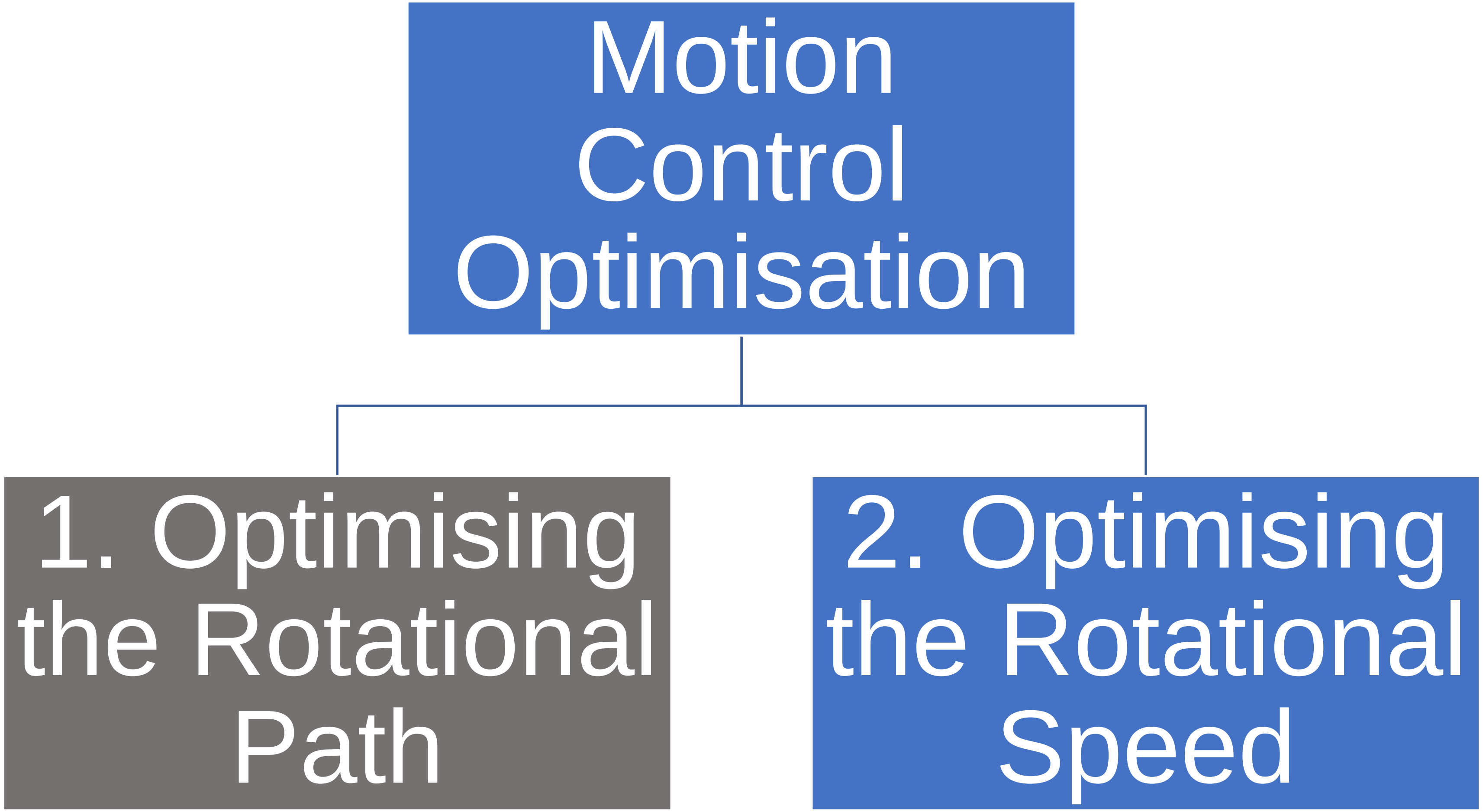




Discussion:

- Moving mould away from secondary axis of rotation decreases the SD of PWCT.
- Highlights compromise between output rate and quality.
- How to obtain both high output rate and high quality?
    - Rotate all moulds through their secondary axis of rotation.

QUEEN'S UNIVERSITY BELFAST



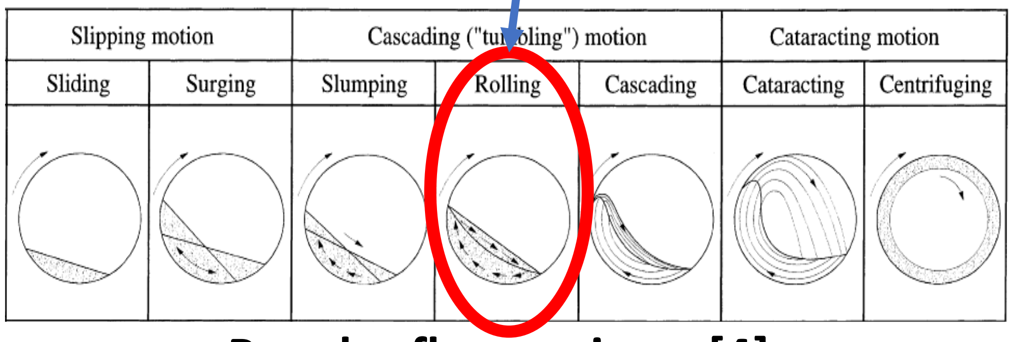
QUEEN'S UNIVERSITY BELFAST

2. OPTIMISING ROTATIONAL SPEED – STATE OF THE ART

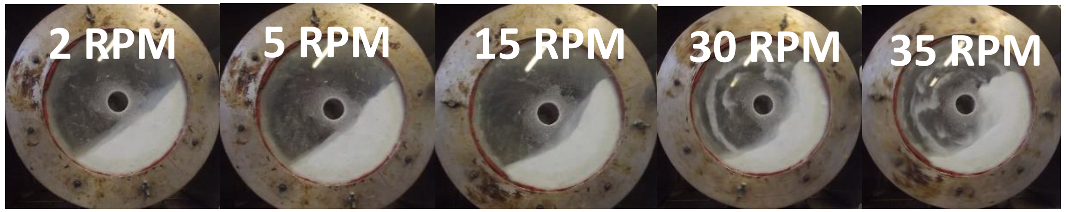
- Moulds rotated between 4-30RPM [3]. **What speed is best?**
- Rotational speed will dictate the flow nature of powder.
  - As well as mould size, powder level, wall friction etc.
- Suggests improvements to cycle time by changing rotational speed during cycle.
- Reduced wall thickness uniformity expected when powder is flowing in a chaotic manner.
- No modelling/simulating tool available to accurately represent effect of rotational speed on wall thickness uniformity.

Rolling regime

- Best for powder mixing and achieving temperature uniformity (expected to improve cycle time).
- Most uniform, consistent flow pattern and expected to provide optimum wall thickness uniformity.



Powder flow regimes [4]



QUEEN'S UNIVERSITY BELFAST

[3] R. J. Crawford and S. Gibson, "Rotational Molding: A Review, "Popular Plastics & Packaging, pp. 19–23, 2015.
[4] J. Mellmann, "The transverse motion of solids in rotating cylinders forms of motion and transition behavior," Powder Technology, vol. 118, no. 3, pp. 251–270, 2001.

2. OPTIMISING ROTATIONAL SPEED:

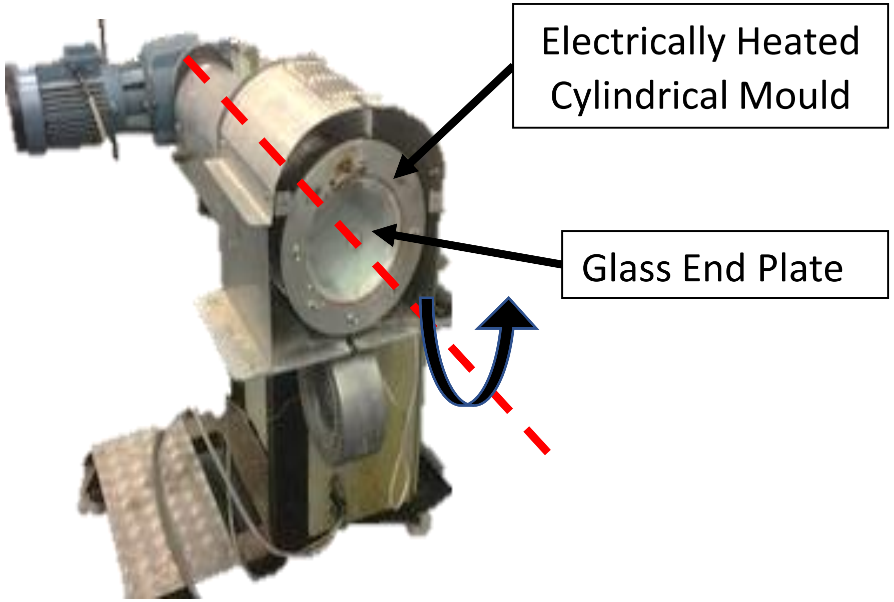
AIM

- Investigate the effect of rotational speed on product quality (wall thickness uniformity) and cycle time by focusing on powder flow behaviour.

OBJECTIVES

- Experimental testing for range of rotational speeds (constant & varied) at 10% and 30% powder fills. (using uniaxial rotomoulding machine and cylindrical mould).
- Evaluate the effect of rotational speed on cycle time and wall thickness uniformity.
- Simulate powder flow to obtain powder-wall contact time (PWCT) uniformity for range of rotational speeds.
- Compare PWCT and wall thickness uniformity.

EXPERIMENTAL METHOD – EFFECT OF ROTATIONAL SPEED ON CYCLE TIME & WALL THICKNESS.



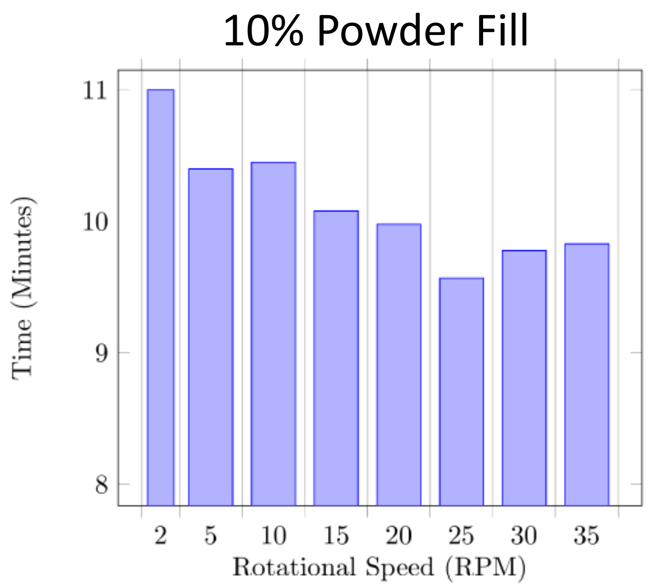
Uni-axial Rotational Moulding Machine

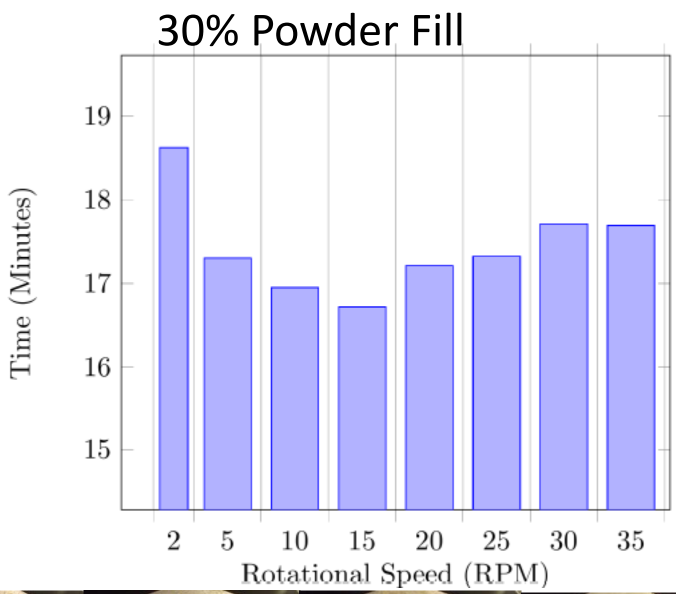
QUEEN'S UNIVERSITY BELFAST

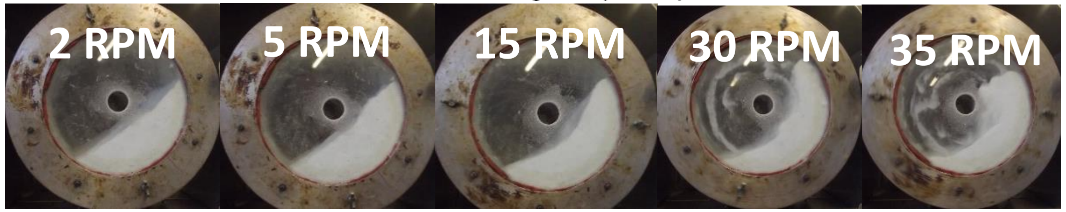
- **Investigate effect of rotational speed using Uniaxial RM Machine.**
  - Medium Density Polyethylene (MDPE) powder loaded inside mould.
    - **10% & 30%** powder fill levels tested.
  - Mould rotation and heating started simultaneously.
    - Constant rotational speed of mould. 2,5,10,15,20,25,30,35 RPM.
    - Rotational **speed varied** based on results from constant speeds tested.
  - **Internal air temperature** (IAT) recorded throughout cycle to monitor key events.
  - Powder flow recorded through glass end plate using high speed camera.
  - Mould cooling begins when IAT reaches 200°C and part demoulded when IAT reached 60°C.
  - Moulded parts cut into 40 test specimens and measured wall thickness.

EXPERIMENTAL RESULTS – MELTING TIME

- Melting time results for constant speeds 2-35RPM.







QUEEN'S UNIVERSITY BELFAST

Discussion:

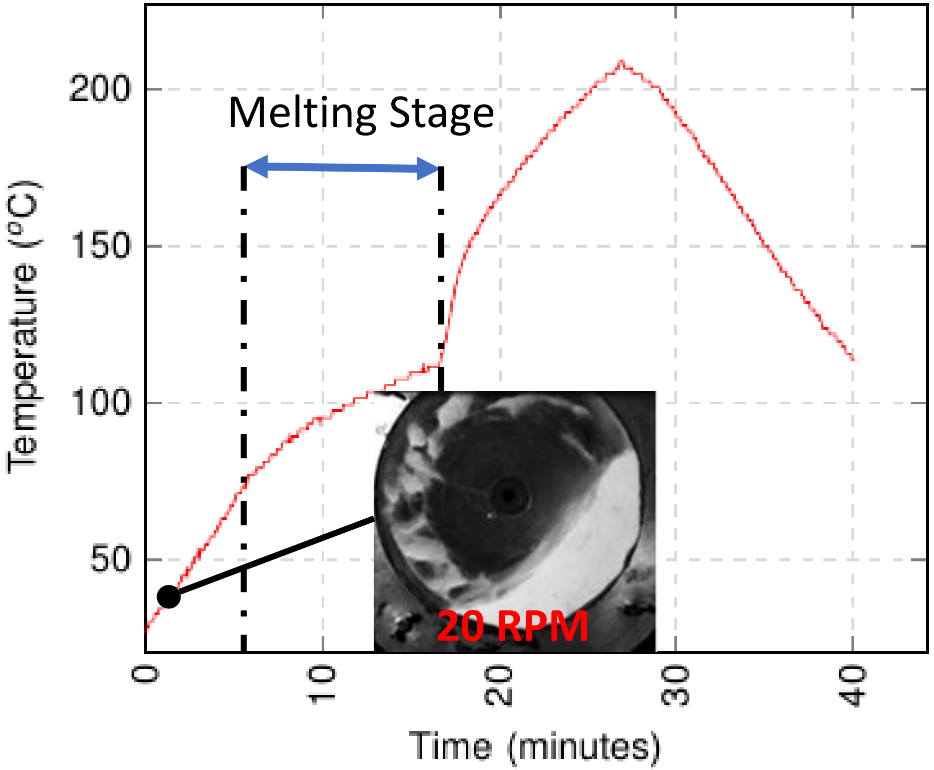
- Melting time longest at the lowest speed, due to lack of powder flow.
- Optimal rotational speed for 10% (25 RPM) powder fill compared to 30% (15RPM).
    - ❑ Contributed to different powder flow motions between two powder fill levels.

EXPERIMENTAL RESULTS – VARIABLE SPEED

- 30% powder fill level.

- Powder flow changes observed during cycle.
  - ❑ Due to increased friction, dropping powder level and cohesion between mould wall and flowing powder during melting stage.

Internal Air Temperature Trace

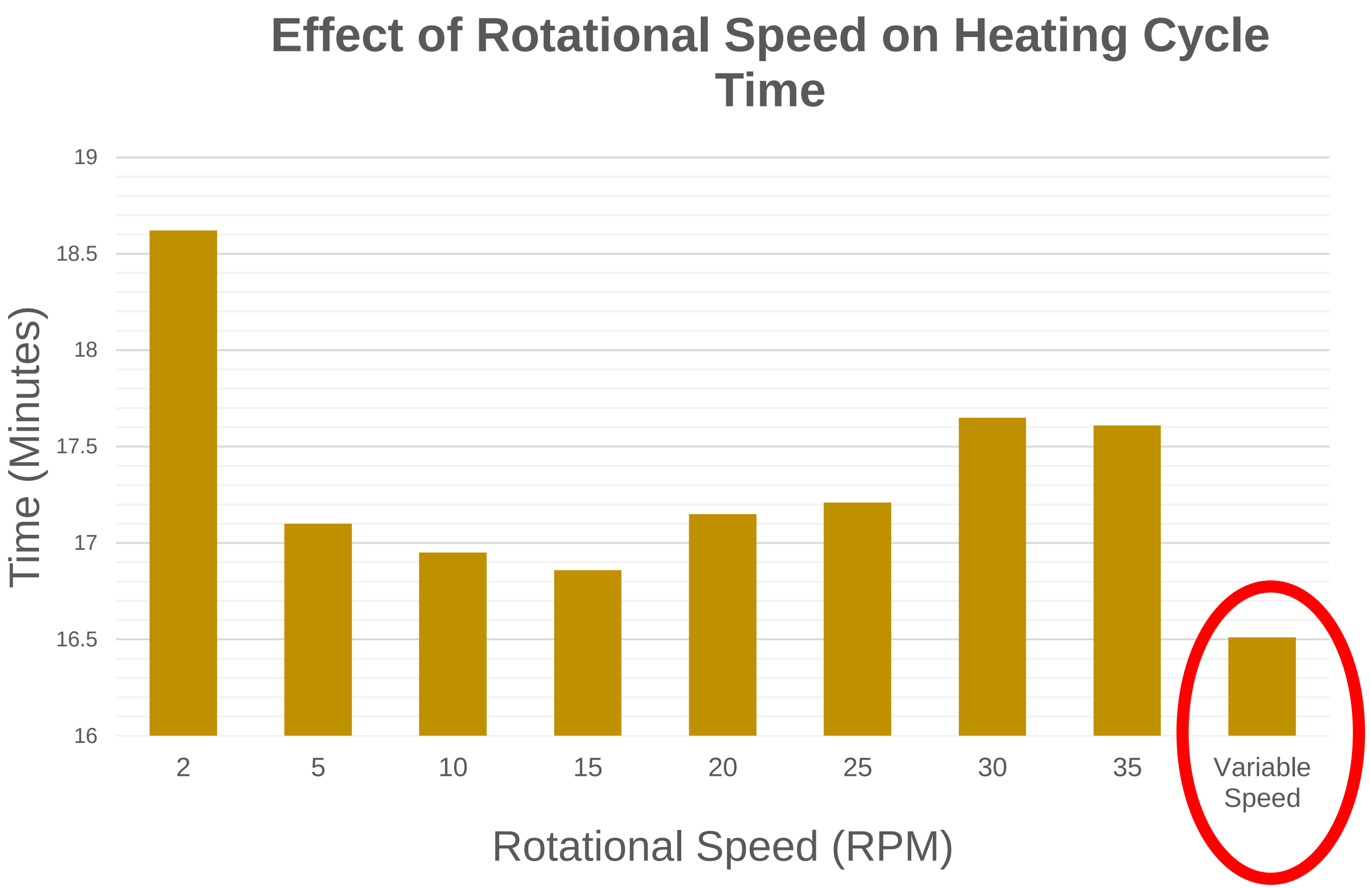


- Strong circulating flow at 20 RPM during induction stage.

QUEEN'S UNIVERSITY BELFAST

EXPERIMENTAL RESULTS – VARIABLE SPEED

- Speed varied to control powder flow.
- Variable speed during cycle found to reduce heating cycle time by up to 2.5%.



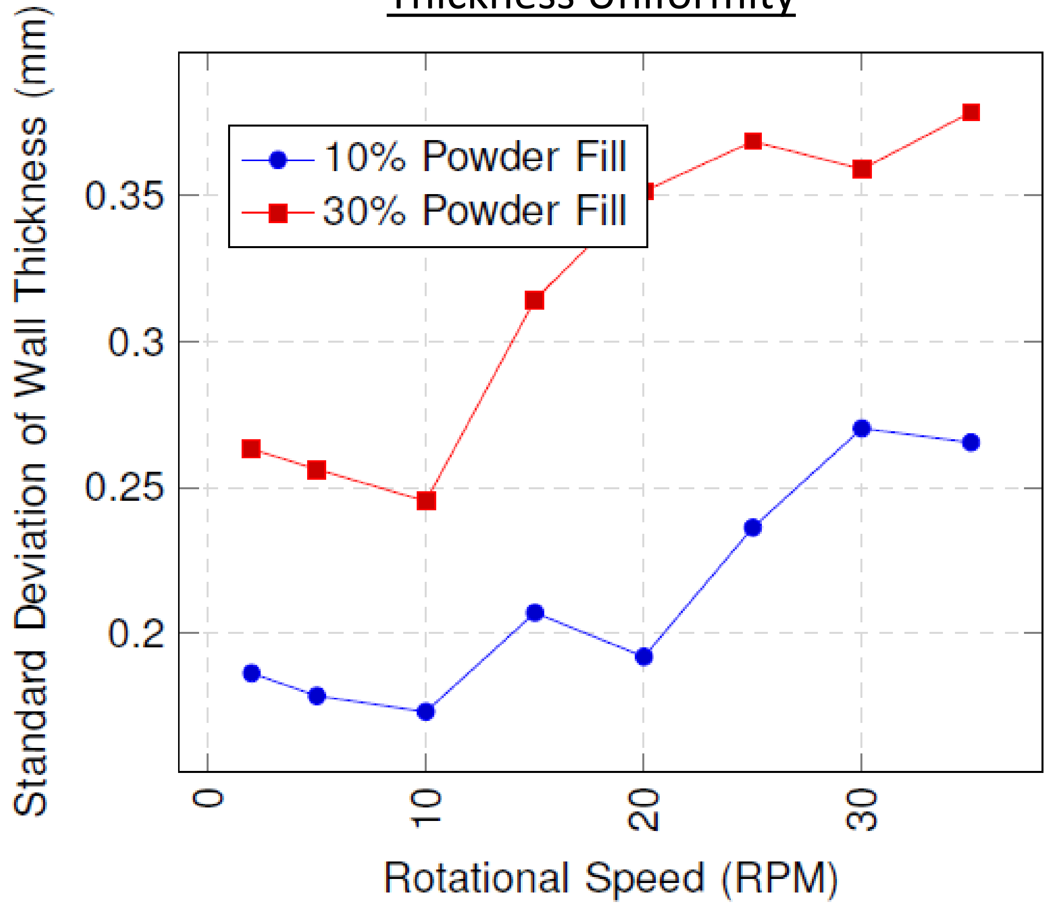
QUEEN'S UNIVERSITY BELFAST

EXPERIMENTAL RESULTS – WALL THICKNESS UNIFORMITY

Discussion:

- Steady reduction in SD between 2-10 RPM.
  - ❑ Powder observed to flow in a more uniform, consistent manner with increasing speed.
- SD increases rapidly beyond 10RPM for 30% fill, and 20RPM for 10% fill.
  - ❑ Contributed to powder flow more chaotically above these speeds (especially at the beginning of melting stage).

Effect of Rotational Speed on Wall Thickness Uniformity



SIMULATION: DISCRETE ELEMENT METHOD (DEM) SETUP

LIGGGHTS®

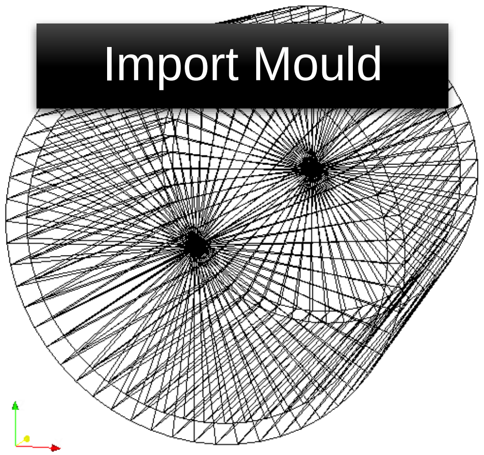
Insert mould

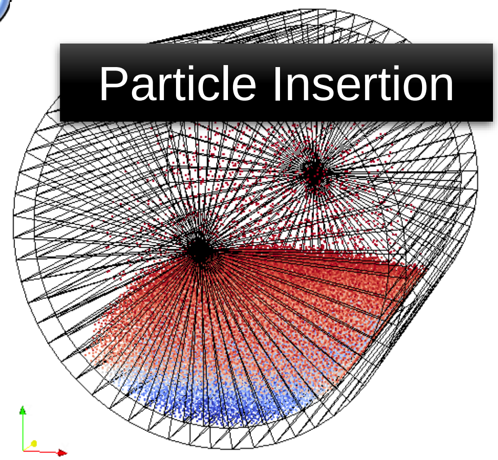
Define particle properties.
- Material: LMDPE
- Density: 0.935 g/cm^3
- Radius: 50-350µm (as per PSD)
- Young's Modulus: 700 MPa
- Poisson ratio: 0.45

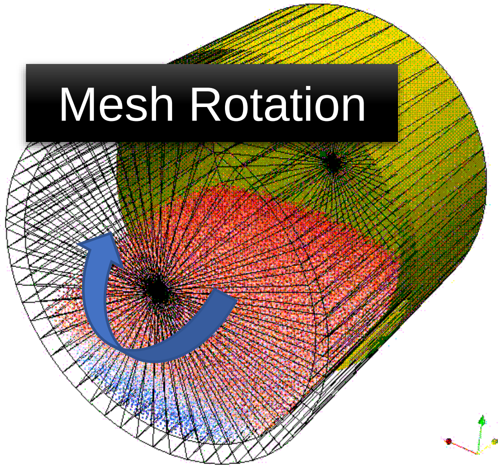
Particle insertion.

Wait
- Allow particles to settle .

Rotation
- Mould mesh rotated about defined y axis.
- **2-40 RPM**





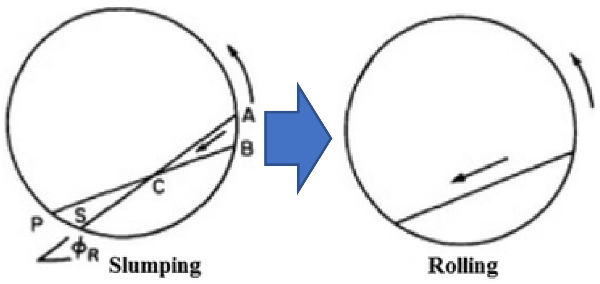


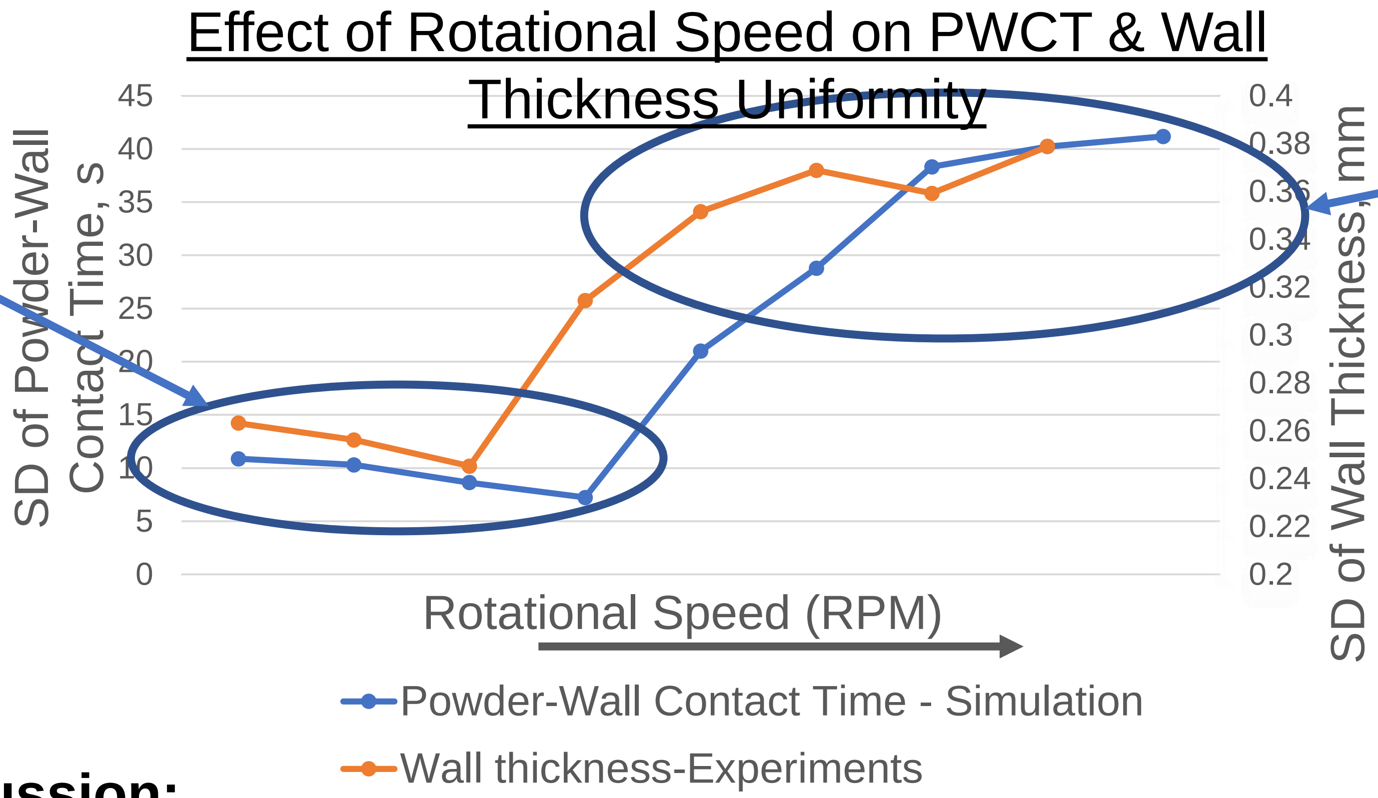
- Contact time between powder and each mould wall element recorded to find contact time uniformity.
  - ❑ Powder-wall contact time (PWCT) uniformity affects the wall thickness uniformity.
- Simulation results (PWCT) will be compared to experimental results (wall thickness).

QUEEN'S UNIVERSITY BELFAST

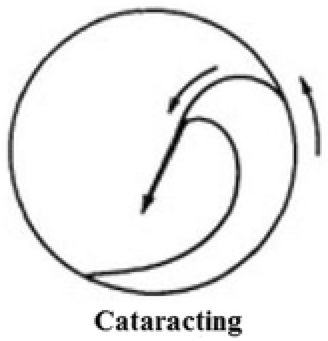
SIMULATION VS EXPERIMENTAL RESULTS – WALL THICKNESS

1. Decreasing SD as powder flowing in more regular pattern.





2. Increasing SD as powder flow becomes chaotic.



Discussion:

- Similar trends in SD between powder-wall contact time (PWCT) and wall thickness found.
  - ❑ Gradual reduction in both SD's during lower speeds confirms that reduction is due to powder flow nature.
  - ❑ Both SD's increase rapid at speeds when the powder observed to become chaotic in nature.

QUEEN'S UNIVERSITY BELFAST

SUMMARY

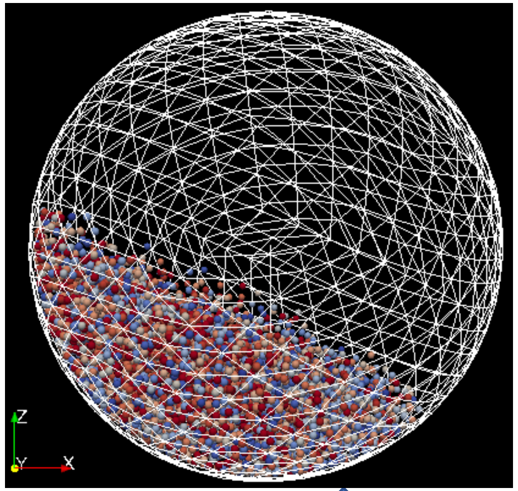
- First steps in implementing Industry 4.0 practices.
- Simulation (DEM) utilised to quantify the distribution of powder within mould.
    - ❑ Wall thickness correlated well with PWCT from simulation.
- Optimising the rotational path found to improve powder distribution by up to 75% achieved.
- Advantages of **variable speed** during melting process investigated.
    - ❑ Reduction in heating cycle time by 2.5% achieved.

QUEEN'S UNIVERSITY BELFAST

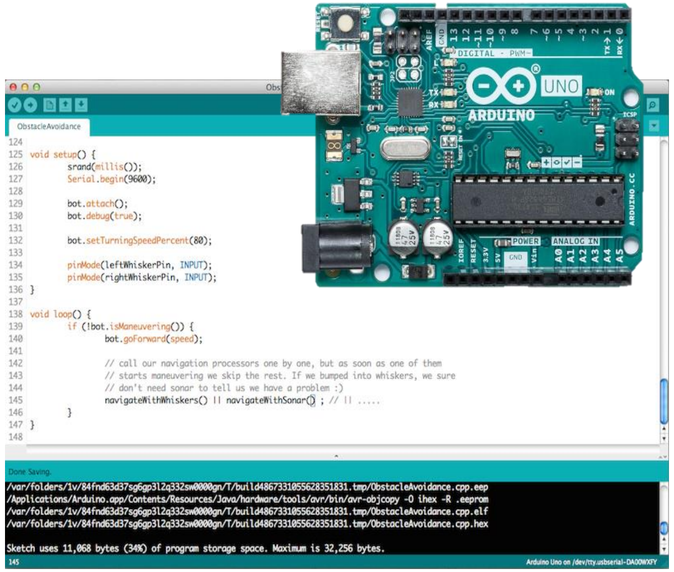
FUTURE WORK

- Development to allow simulation results to drive automated/robotic machines to enable Industry 4.0 implementation.

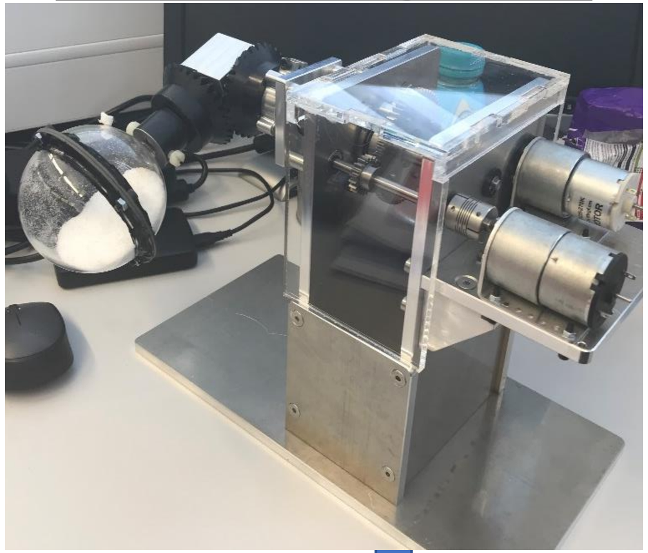
Simulation



Arduino Control system



Smart Desktop Rotomoulding Robot



Feedback

QUEEN'S UNIVERSITY BELFAST

ACKNOWLEDGEMENTS

PPRC 20

Department for Employment and Learning
www.delni.gov.uk

Institution of MECHANICAL ENGINEERS

QUEEN'S UNIVERSITY BELFAST

THANKS FOR LISTENING.

QUEEN'S UNIVERSITY BELFAST

CONTACT INFORMATION

EMAIL: jadams25@qub.ac.uk

PHONE: +44(0) 7903893842

QUEEN'S UNIVERSITY BELFAST