OPTIMOS PRIME:

Organising **P**roduction **T**echnology **I**nto **MO**st Responsive

States - 3D **PRI**nt **M**achine **E**nabled Networks

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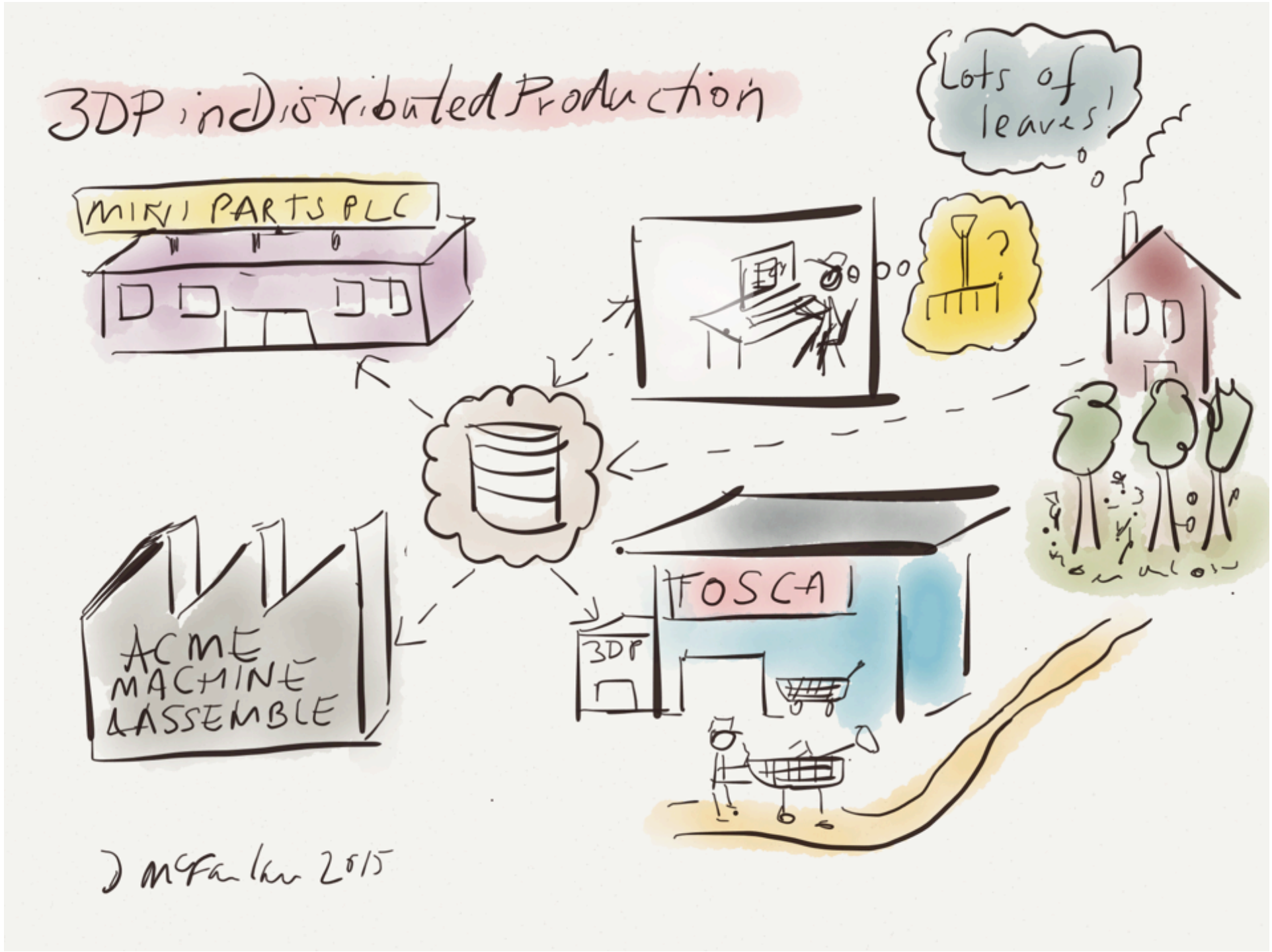
3DP – RDM WORKSHOP

Cambridge, 14 January 2016

Contents

- Introduction
- Aims, Objectives, Approach
- Industrial Practices
- Academic Literature
- Control Requirements & Architectures
- Experimental Study
- Going Forward


3DP : in Distributed Production
Lots of leaves!
MINI PARTS PLC
FOSCA
3DP
ACME MACHINE ASSEMBLE
D McFarlane 2015

Introduction

- Challenges in distributed manufacturing supply networks:
  - Lean for cost and efficiency
  - Responsiveness to disruptions
- Increasing need to evaluate additive manufacturing capability for:
  - Flexibility and responsiveness
  - Reconfigurability
  - Customisation
  - Understanding the ability to integrate with conventional manufacturing systems

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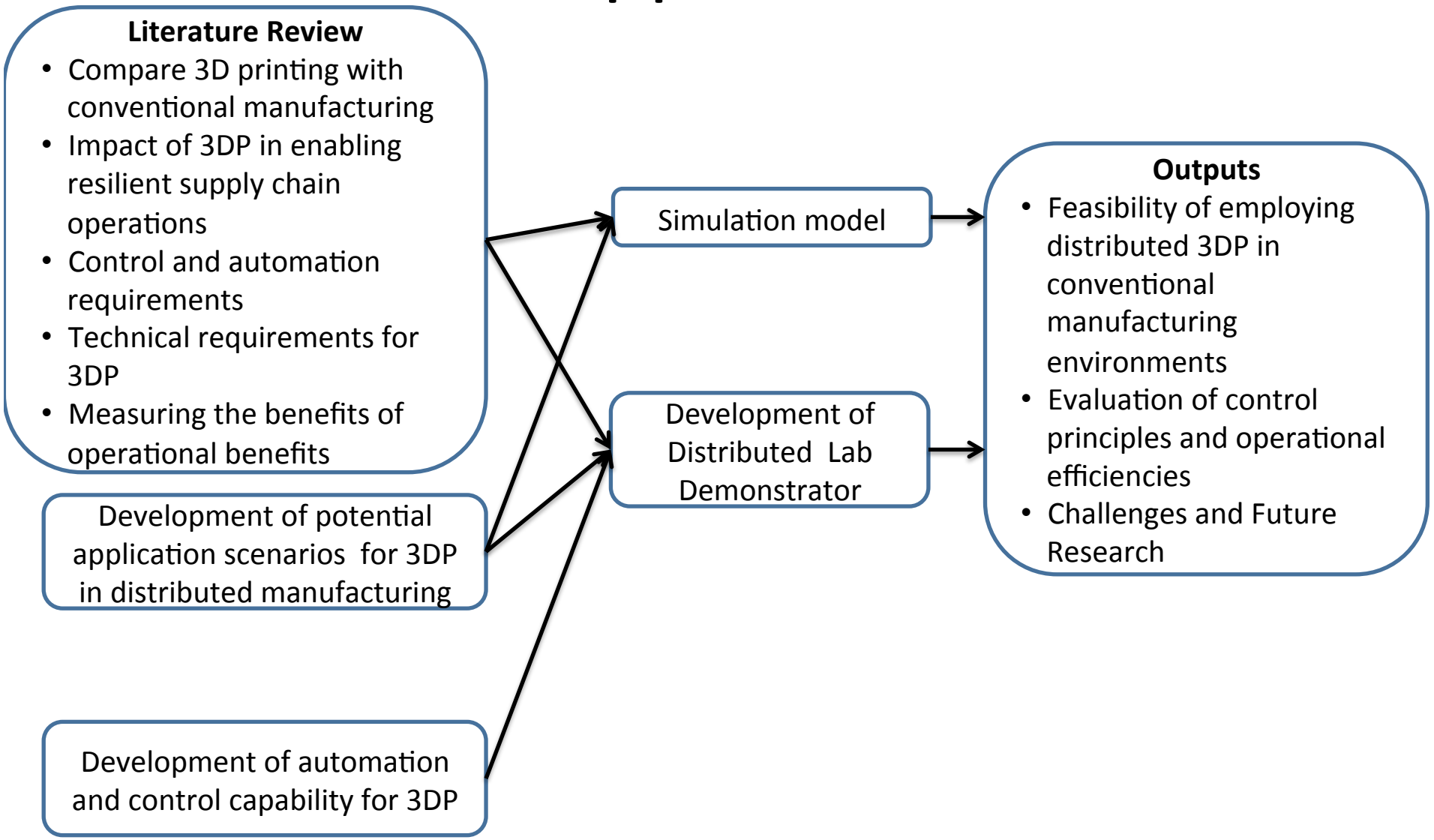
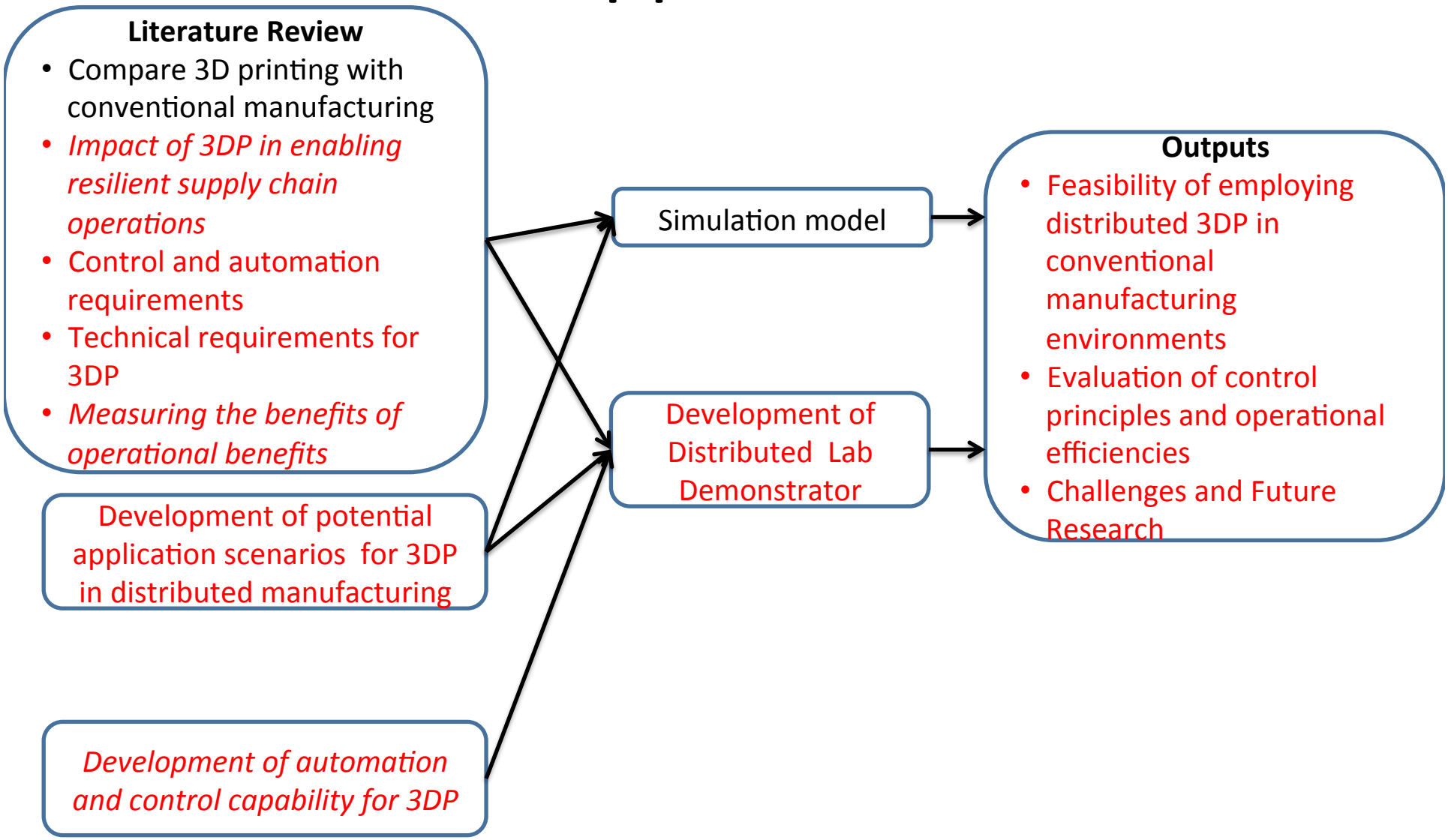
Aims and Objectives

- How can 3D print enabled distributed manufacturing environment provide rapid response capability?
  - How effectively can 3D printing be used to add rapid response capabilities to conventional production?
  - How can 3D printing support 3rd party spares and repair services in tandem with a production facility?
  - How can late customisation carried out by retailer be part of an integrated production process?
  - *(iv) How can distribution of production facilities be managed within a single [cloud based] production control system?*

Approach


Literature Review
• Compare 3D printing with conventional manufacturing
• Impact of 3DP in enabling resilient supply chain operations
• Control and automation requirements
• Technical requirements for 3DP
• Measuring the benefits of operational benefits
Development of potential application scenarios for 3DP in distributed manufacturing
Development of automation and control capability for 3DP
Simulation model
Development of Distributed Lab Demonstrator
Outputs
• Feasibility of employing distributed 3DP in conventional manufacturing environments
• Evaluation of control principles and operational efficiencies
• Challenges and Future Research

Approach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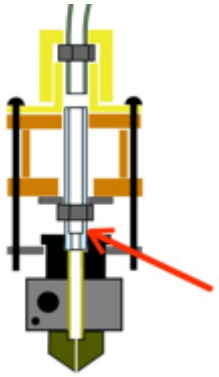
Industrial Practices Overview

- Focus only on aspects of todays developments & practices which impact on
  - Integration
  - Automation
  - Controllability

- Not a comprehensive 3DP review!

AM Approaches & Integratability

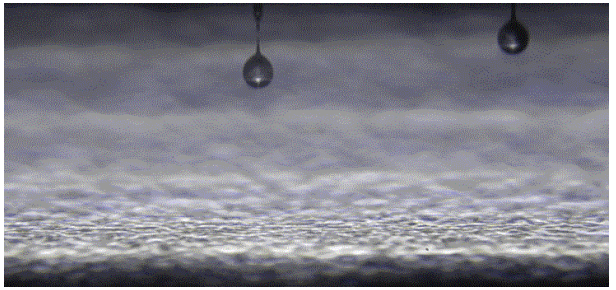
	Speed	Accuracy	Finish	Range
Binder jetting	Y		N	Y
Directed energy deposition		Y	?	
Material extrusion				Y
Material jetting		Y		N
Powder bed fusion			Y	



Extrusion

Adapted from
www.ultimaker.com

Jetting



[Inkjet Research Centre, IfM]

Automation Readiness

- Many challenges specific to each AM technique in *material management*, *component removal/transfer*, *post-processing*, *validation*
- Fixturing/Sensing capabilities to track operations
- support material in 3D printed parts -> impact on automation
- *Ongoing moves to support distributed manufacturing by automation:*

"Three Signs that the Fully Automated 3D Printing Factory Is Coming"
Davide Sher, 3D Printing Industry, 2015

"Louisville factory: 100 printers, 3 employees"
Parija Kavilanz, CNNMoney, 2015.

"How CloudDDM Is Putting Speed and Automation Into 3D Printing"
Josh Mings, SolidSmack, 2015

[A. Wheeler, "CloudDDM's New Strategic End-of-Runway 3D Printing Service", Engineering.com, July 30th 2015.]

Comms & Control Potential

Communication

- Need for networking/communication facility
- Ability to communicate within and outside organisational boundaries (inter/intra network capability)
- Need for standard interfaces for communication (TCP/IP, EtherCat etc) to integrate with conventional devices/technologies

Interfaces/ Control

- Limited capability for software development/ control interfaces to execute and monitor tasks in 3DP
- Conversion of CAD related files into 3D printer enabled g-codes are not standardisedLimited Ability to control/communicate with 3D printer varies between manufacturers (open source development Vs proprietary tools)

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Literature Overview

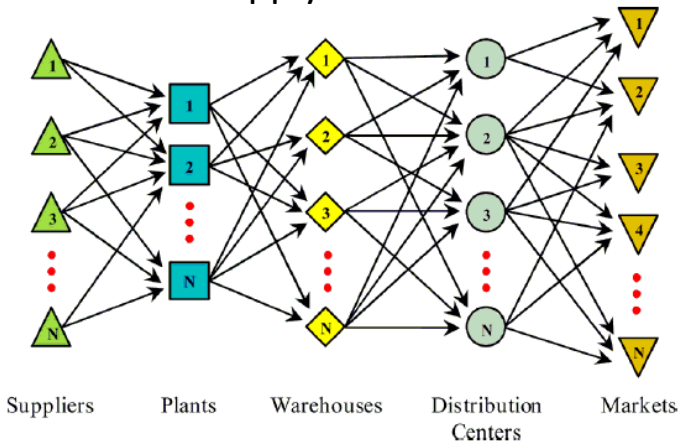
- Vast literature on 3DP / AM technologies and capabilities c.f. conventional
- Little or no literature on control / automation of 3DP / AM technologies
- Little or no literature on integration of 3DP with conventional manufacturing
- Significant literature [not 3DP specific] on
  - distributed production network design
  - Distributed production control and
  - Lean v / resilience in distributed supply chains

Practice slightly ahead of literature

e.g. Optimal Network Design

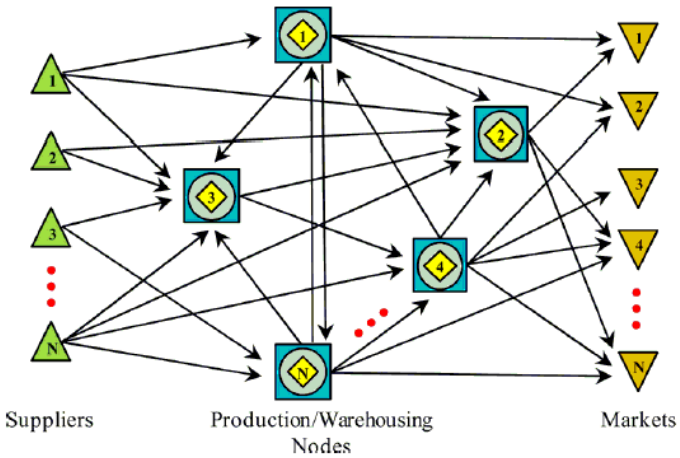
Optimal design of distributed networks [including 3DP facilities]	**Location: offshoring vs reshoring**	**[4] Da Silveira, G.J.C. (2014). An empirical analysis of manufacturing competitive factors and offshoring. *International Journal of Production Economics* 150, 163–173.** [5] Gylling, M., Heikkilä, J., Jussila, K., and Saarinen, M. (2015). Making decisions on offshore outsourcing and backshoring: A case study in the bicycle industry. ***International Journal of Production Economics*** 162, 92–100. [6] Ellram, l.M., Tate, W.L., and Petersen, K.J. (2013). Offshoring and Reshoring: An Update on the Manufacturing Location Decision. *Journal of Supply Chain Management* 49 (2) **[7] De Treville, S., Trigeorgis, L. (2010). It may be cheaper to manufacture at home. *Harvard Business Review* 88, 84–87.**
	Optimal number and location of resources	[8] Kalaitzidou, M.A., Longinidis, P., Tsiakis, P., and Georgiadis, M.C. (2014). Optimal Design of Multiechelon Supply Chain Networks with Generalized Production and Warehousing Nodes. *Industrial & Engineering Chemistry Research* : 53 (33), 13125-13138. [9] Pasandideh, S,H.R., Niaki, S.T.A., and Asadi, K. (2015) Optimizing a bi-objective multi-product multi-period three echelon supply chain network with warehouse reliability. *Expert Systems with Applications* 42(5), 2615-2623.
	Optimal flow in the network	[10] Ventuta, J.A., Valdebenito ,V.A., and Golany, B. (2013). A dynamic inventory model with supplier selection in a serial supply chain structure. *European Journal of Operational Research* 230(2): 258-271.
	Flexibility (cap'y reallocation)	[11] Rosenbaum, I., Ben-Gal, I., and Yechiali, U. (2013) Node generation and capacity reallocation in open Jackson networks. *IIE Transactions* Vol 45, Number 3, 259-272.

Mainstream supply chain network structure



Innovations:
1) Generalized P/W nodes whose function is not a priori assumed
2) Collaboration among P/W nodes

Generalized structure



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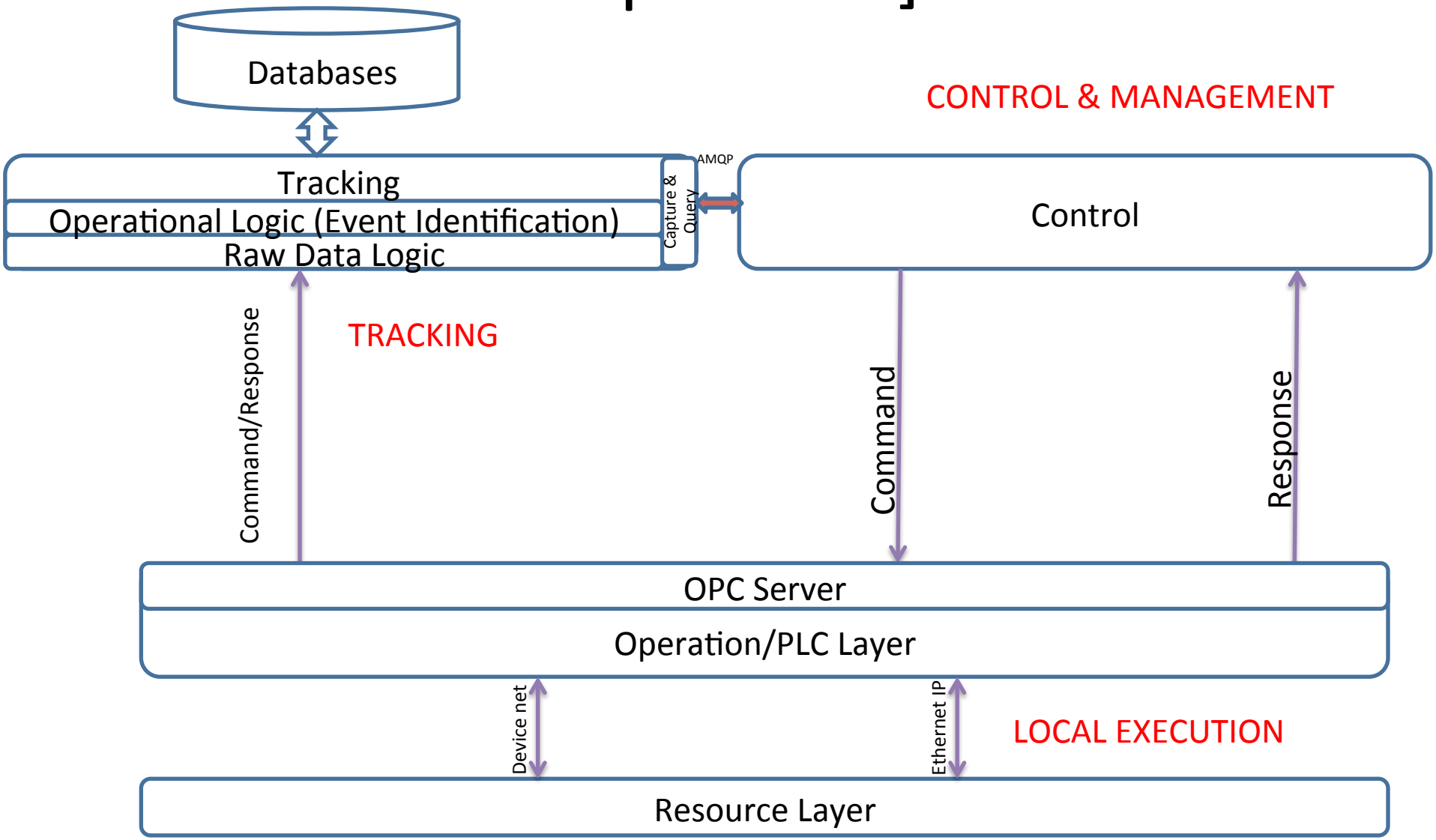
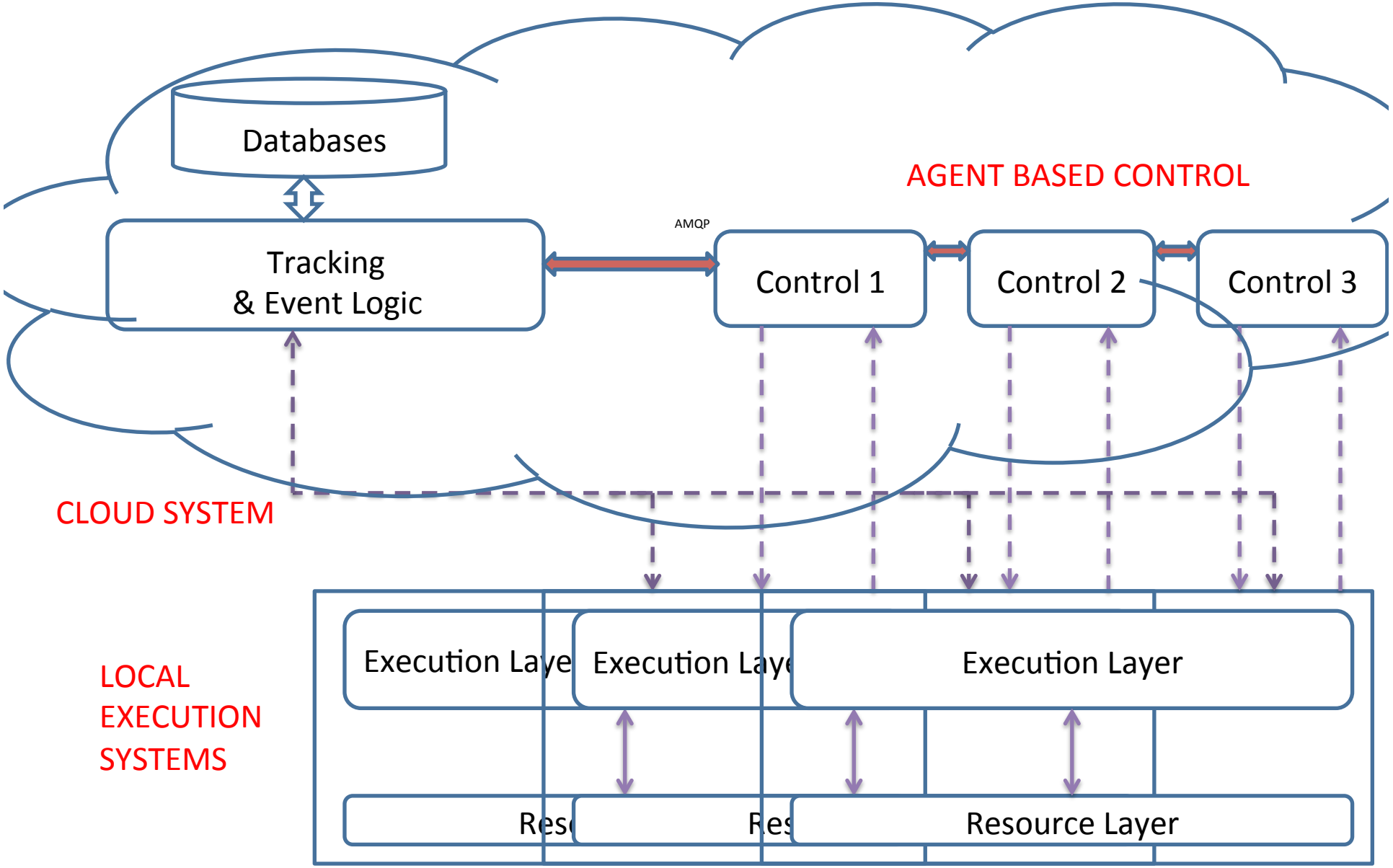
Control Requirements for 3DP in Distributed Production Network

- **(R1) Cooperation** — Effective communication b/w 3D printers on a network and ability to resolve conflicts
- **(R2) Flexibility** — Control feature that offers little change-over time/effort
- **(R3) Re-configurability of Operations** — Change of operations over time/order
  - Tackle disruptions (delays on a 3DP) and the option to re-configure the network to meet goals (delivery time)
  - Prioritisation— fulfil subsequent orders (instead of waiting for 10units of plastics, make use of the available 8 to meet 2 other orders requiring 3 and 2 units only)
- **(R4) Self-organisation Capability**
  - Autonomously accommodates a change in due date/rush order/quicker delivery/ premium quality of some parts.
  - Autonomously accommodates late customisation request that cannot be produced by a single facility on its own.
- **(R5) Seamless integration:**
  - Level 1 - Distributed operation within company
  - Level 2 - Distributed operation involving multiple companies.

Initial System Architecture [Single Operation]



Target Distributed System Architecture



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Application Scenarios

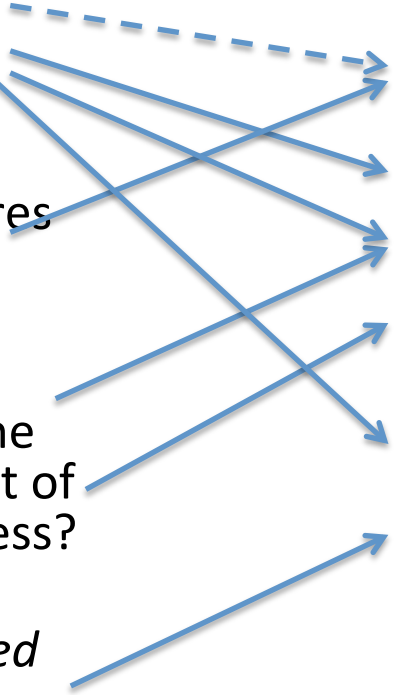
Objectives

(i) How effectively can 3D Printing be used to add rapid response capabilities to conventional production?

(ii) The extent to which 3D Printing supports 3rd party spares and repairs services in tandem with a production facility?

(iii) The extent to which late customisation carried out by the retailer for example can be part of an integrated production process?

(iv) How can distribution of production facilities be managed within a single [cloud based] production control system?



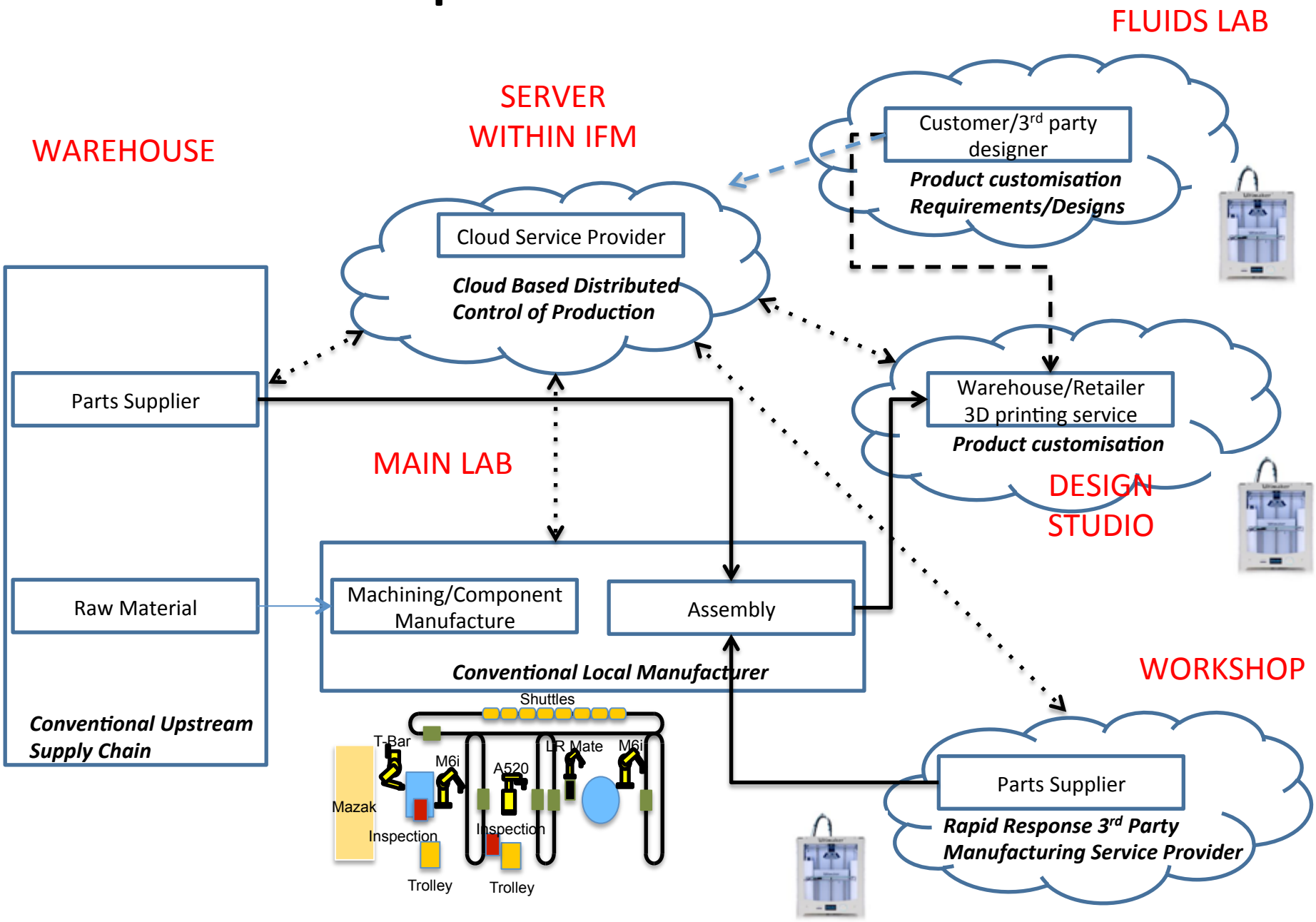
Scenarios

Spare part management in production
Reactive part replacement
Customisation of product
Late Customisation of product
All

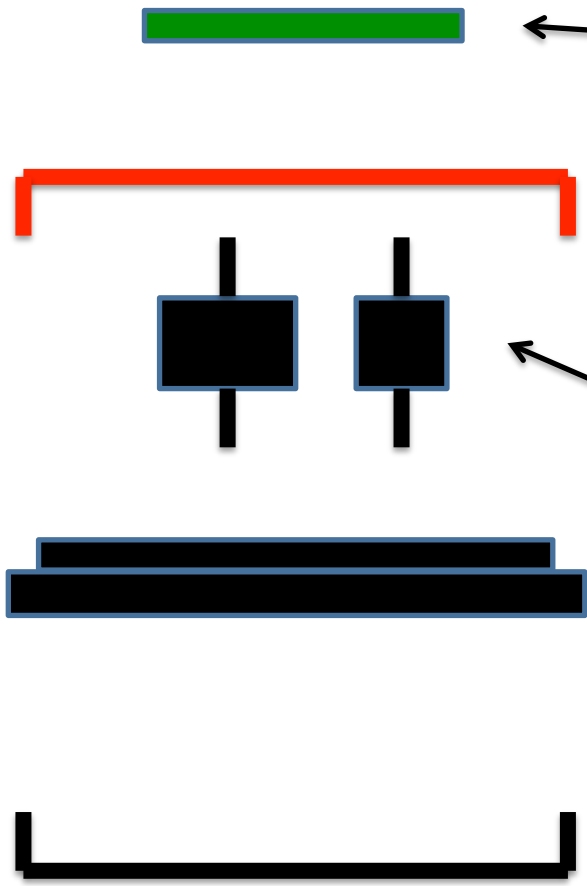
Example: Product Customisation

- An order for ten gear boxes arrives
- Eight gear boxes will use conventional gear pairs
- Four of these are required to have a coloured cap attached to the gear box with the letter M
- Two gear boxes will use non standard gear sets [although usual shaft positions]
- 3DPa can manufacture both required set of gears but is expensive
- 3DPb can produce the smaller but not the larger gear.
- 3DPb can produce the coloured caps required
- The products are required to be assembled in one week
- There is nowhere to store the coloured caps so they need to be produced JIT
- The customer requires 100% inspection of the two non standard gear boxes.

Test Implementation at IFM



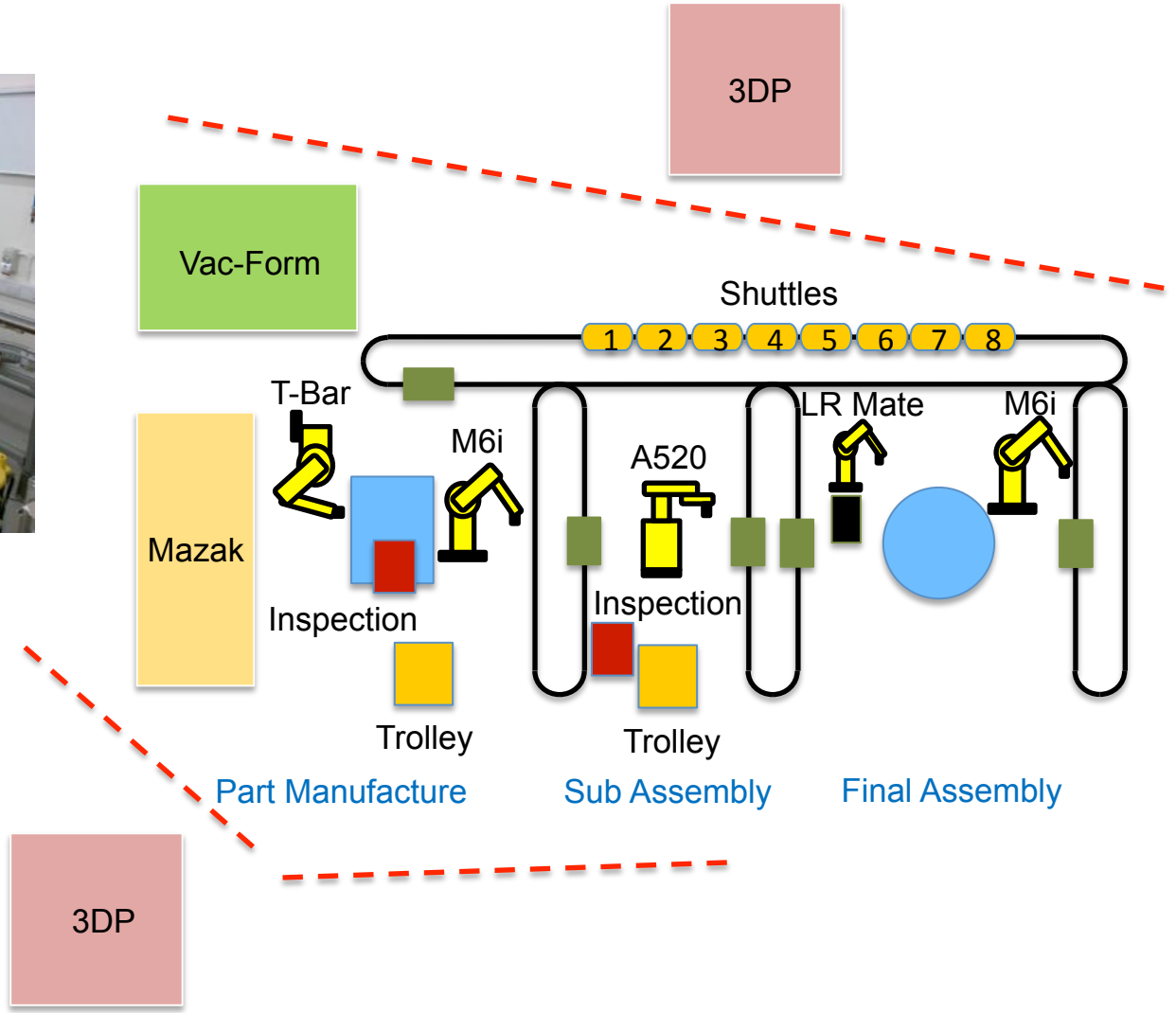
Product Customisation



Customisable
name plate
On gear box

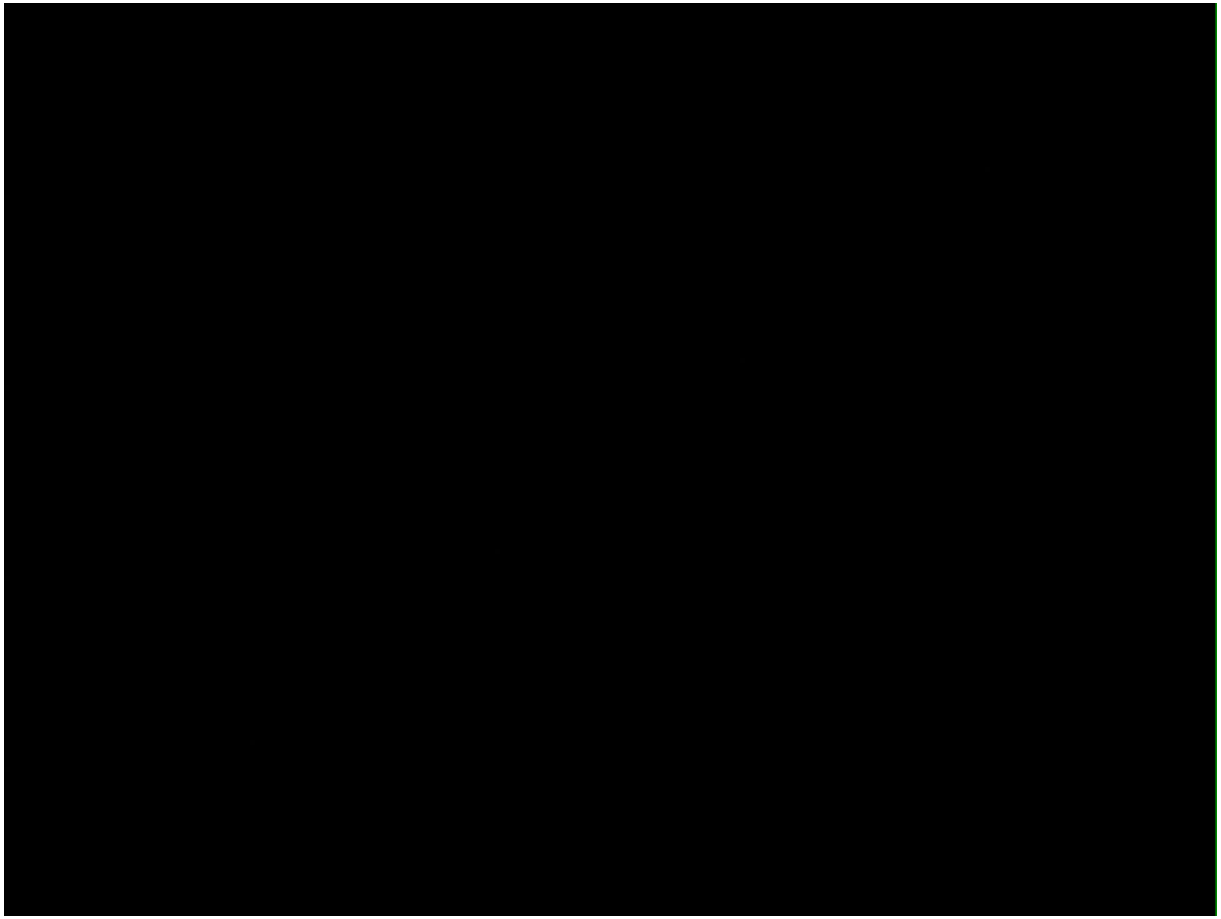
Plastic or
metal gears

Proof-of-concept Demonstration



Proof Of Concept Demonstration

- Demonstrations
  - Gear Printing
  - Gear Box Assembly
  - Late Gear Box Customisation



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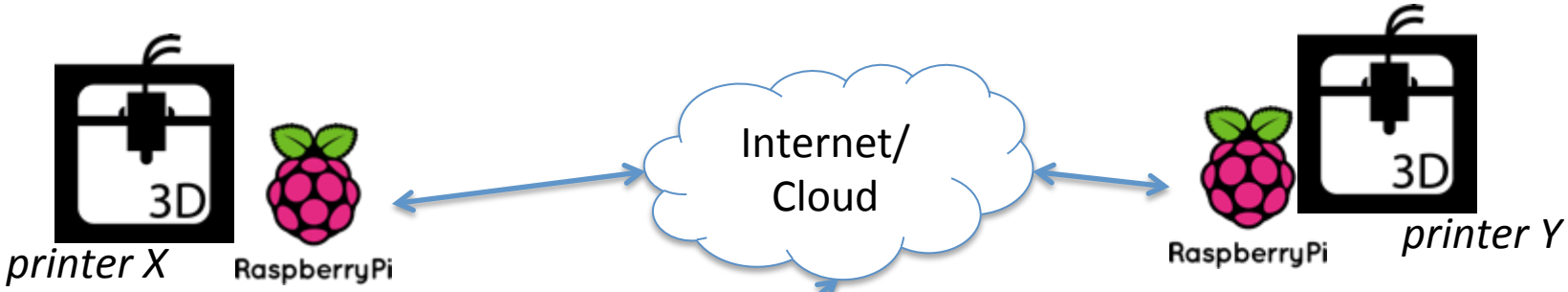
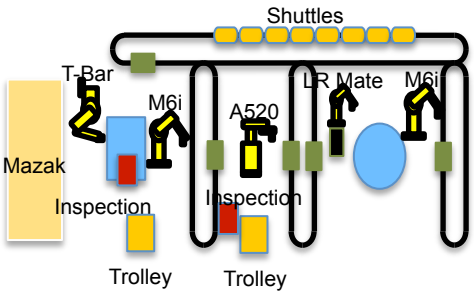
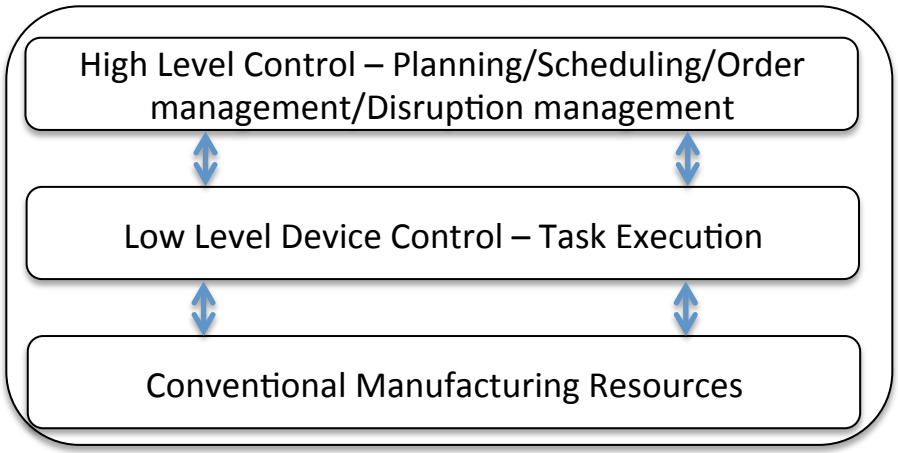
Demo Control Architecture





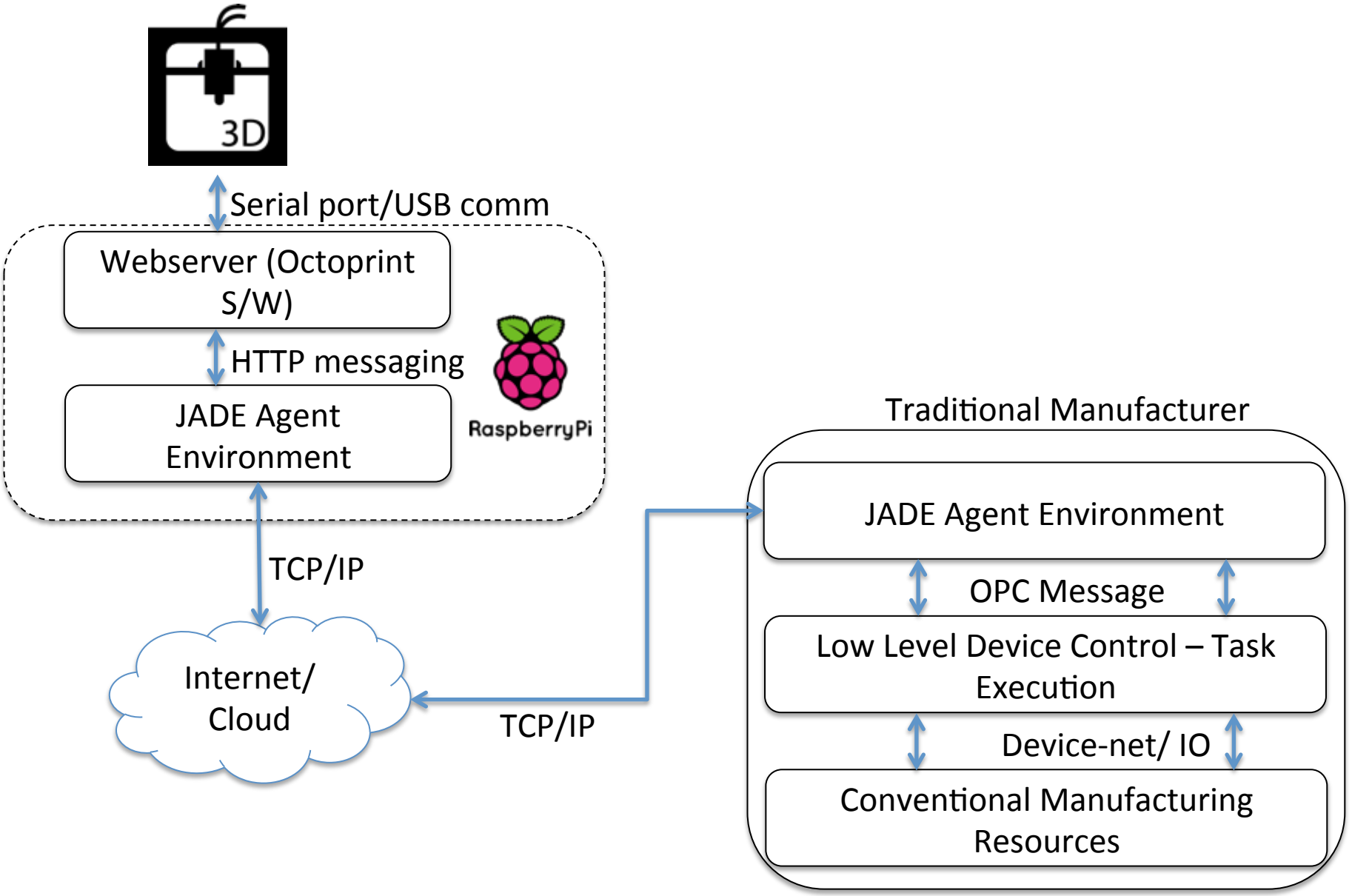
a. Selection of suitable 3D printer firm/ Supplier management
b. Decision/Choice to decide when to order rush parts
c. Customisation management



Traditional Manufacturing Control Architecture

- Distributed control
- Centralised/Hierarchical control
- Hybrid/Semi-heterarchical control

3DP – Conventional: control Interface



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Next Steps

- Further developments of distributed lab demonstrator
  - Development of distributed intelligent control
  - Assessment of additional scenarios and operational efficiencies.
- Modelling of resilience in distributed manufacturing environments enabled by 3DP
- Larger proposal to investigate 3DP integration / automation / cloud control requirements & limits

Simulation of 3DP and conventional manufacturing