Defining the Research Agenda for 3D Printing-Enabled Re-distributed Manufacturing

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Abstract. Advanced manufacturing technologies are changing how and where goods are produced, with established organisational practices and value chains being disrupted by the adoption of these technologies. The 3DP-RDM network has been created to explore the changes caused by such technologies, focusing on the emergence of 3D printing and the effects it is having on the re-distribution of manufacturing. This paper reports on the first activities of this network, describing the process used in a multi-disciplinary scoping workshop and the selection criteria for the feasibility study competition, and how these help to achieve the network achieve its objective of defining the research agenda for 3D printing-enabled re-distributed manufacturing.

Keywords: 3D printing · Additive manufacturing · Re-distributed manufacturing · Research agenda

1 Introduction

Advanced manufacturing technologies are changing how and where goods are being produced. One of these technologies, 3D printing (3DP, also known as additive manufacturing), offers the prospect for on-demand, mass personalisation, localised, flexible and more sustainable production. The ability to manufacture goods only when needed, closer to the point of consumption and in response to consumer needs has enormous ramifications for established organisational practices and value chains.

While advances are being made to the technical capabilities of 3DP, the impact of adopting these technologies remains highly uncertain. The 3DP-RDM network has been created in an effort to better understand their implications and how 3DP could enable re-distributed manufacturing (RDM). The objectives of this network are to develop an improved understanding of the research challenges that lie at the intersection of 3DP and RDM, and to define the agenda for future research in this area.

This paper reports on the first activities of the 3DP-RDM network. It documents the process that was used at the first scoping workshop in January 2015 to identify potential feasibility studies. Due to space constraints, sample outputs from the workshop are included in this paper with links to the full data provided. This paper also provides an overview of the process and selection criteria used in the feasibility study

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competition that followed. In reporting on this overall process we show how the initial steps have been made to define the 3DP-RDM research agenda.

2 3D Printing and Re-distributed Manufacturing

3D printing describes a range of additive manufacturing processes that have recently begun to be applied in direct manufacturing. In the UK, their societal and economic importance has been identified in a number of recent reports, with the TSB defining it as one of the UK's 22 priority process technologies [1], and the Government Office for Science expecting 3DP to have "*a profound impact on the way manufacturers make almost any product*" [2]. As the latter report commented, additive manufacturing "*will become an essential 'tool' allowing designs to be optimised to reduce waste; products to be made as light as possible; inventories of spare parts to be reduced; greater flexibility in the location of manufacturing; products to be personalised to consumers; consumers to make some of their own products; and products to be made with new graded composition and bespoke properties*" [8]. The report recommended that greater efforts should be made to understand key technologies such as 3DP in order to guide policy.

Re-distributed manufacturing has been defined by the Engineering and Physical Sciences Research Council (EPSRC) as: "*Technologies, systems and strategies that change the economics and organisation of manufacturing, particularly with regard to location*" [3]. The increased maturity and applicability for manufacturing of 3D printing (3DP) technologies [4, 5] and their resulting diffusion is one factor that may accelerate the re-distribution of some manufacturing activities [1, 6, 7]. "*Companies are re-imagining supply chains: a world of networked printers where logistics may be more about delivering digital design files – from one continent to printer farms in another – than about containers, ships and cargo planes*" [8]. The resulting vision of 3DP wider adoption is that: "*The factories of the future will be more varied, and more distributed than those of today* […] *The production landscape will include capital intensive super factories producing complex products; reconfigurable units integrated with the fluid requirements of their supply chain partners; and local, mobile and domestic production sites for some products. Urban sites will become common as factories reduce their environmental impacts. The factory of the future may be at the bedside, in the home, in the field, in the office and on the battlefield*" [2].

There is a growing realisation of the ways in which 3DP could lead to RDM. However, the impact of 3DP on RDM and vice versa will depend on a variety of interconnected aspects that go beyond the technical performance issues. These include:

1. Economics: the economics of 3D printing, including assessment of the cost advantages and disadvantages;
2. IP: the protection of intellectual property and value appropriation, particularly the protection of copyrights and design rights;
3. Materials: attributes such as quality, durability and recyclability;
4. Skills: the education and development of a 3DP-skilled labour market;
5. Standards: manufacturing standardisation.

A number of recent policy reports have acknowledged the connections between the issues of 3DP and RDM [1, 6, 9]. Despite these connections being acknowledged, the implications and their feasibility remain largely unexplored. The knowledge in the technical, economic and social issues and the dependencies between them that could support industry, policymakers and funding agencies is still fragmented and siloed within specific academic disciplines.

2.1 3DP-RDM Network[1]

The 3DP-RDM network was created due to the growing significance of these manufacturing trends. It was granted funding by the EPSRC/ESRC under its "Re-distributed manufacturing Networks" theme in November 2014 and its activities began in January 2015. The core research issue of the network is to understand the connections between the diffusion of 3DP technologies and RDM (as shown in Fig. 1).

Specifically, the network seeks to understand:

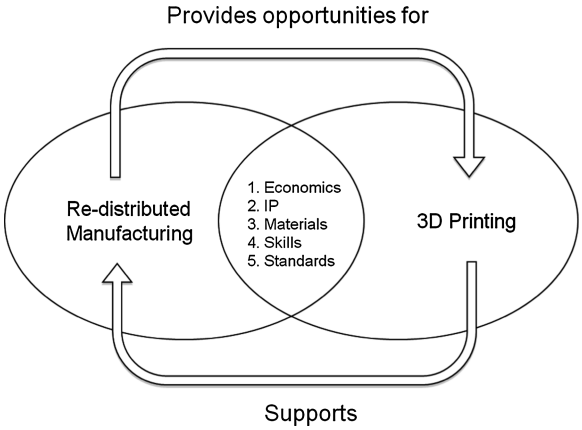

Fig. 1. The conceptual logic for the 3DP-RDM network

1. The features of 3DP technologies that help enable re-distributed manufacturing;
2. How re-distributed manufacturing may accelerate the diffusion of 3DP technologies and vice versa;
3. Sector specific and generic aspects of 3DP enabled re-distributed manufacturing.

These research objectives will be achieved by convening a multi-disciplinary research and multi-industry user community that provides the required breadth and depth of research capabilities to define and disseminate the research agenda for RDM focused around the emergence of 3DP. Specifically, the network involves active

[1] The authors of this paper are the Network Coordinator and Principle Investigator of the 3DP-RDM network respectively.

engagement of this community through scoping workshops and the identification and delivery of six targeted feasibility studies.

In fulfilling our objectives we will develop an improved understanding of the interaction between 3DP and RDM, providing an essential input to the research council's wider goal of defining the research agenda for RDM.

3 3DP-RDM Scoping Workshop

As a first step in establishing the research agenda in 3DP-RDM, a scoping workshop was organised on 30th January 2015 at the Institute for Manufacturing in Cambridge, UK. The workshop involved 37 participants from academia and industry. Its objectives were to identify potential feasibility studies and to facilitate networking because participants were from a wide range of disciplines. To achieve these aims the workshop was organised into the three processes described in the following sections.

3.1 The Identification of 3DP-RDM Research Topics[2]

On arrival at the workshop, participants were assigned to tables to create multi-disciplinary groups of 5-6 people. For the first discussion activity seven groups were created and given the task of answering the question: "*What are the research issues at the intersection of 3D printing and re-distributed manufacturing?*" They were given pens, Post-it notes and the template shown in Fig. 2 to structure the discussion. Towards the end of their discussions, the groups were instructed to identify the top five research topics that they thought needed to be investigated.

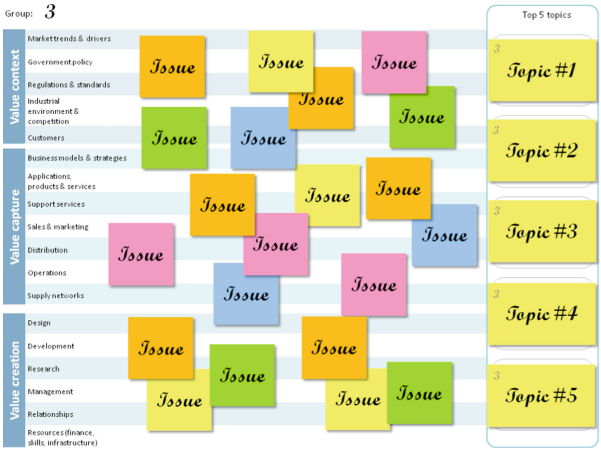

Fig. 2. Template used to facilitate small group discussion and identify potential research topics

[2] Full results can be found here: https://capturingthevalue.wordpress.com/2015/02/05/3dp-rdm-scoping-workshop-discussion-activity-1-outputs/.

3.2 The Prioritisation of 3DP-RDM Research Topics

Following the small group discussion, representatives from each group described their top five research topics to the whole group, with the Post-it notes detailing these placed onto a larger 'landscape' map that resembled the template and which everyone could see. Where possible, similar topics were clustered together on the map in real-time. With seven groups, this resulted in the placement of 35 Post-its.

Once these Post-its were all placed on the landscape map, each participant was invited to vote for those topics they thought should be investigated through feasibility studies during this first year of the network. Each participant was given five dot stickers to place on the topics on the landscape map. The only rule they were given was that they could not place more than one vote for any one research topic. Table 1 provides a list of the top ranked research topics that was generated from this process.

Table 1. Prioritised research topics

Research topic	Votes
Standards + compatibility + regulation + certification //avoidance + convergence?	12
How will value be created and captured in the 3DP-RDM economy?	12
To research gap between hardware (very advanced) and design methods and tools: there is no CAD conceptually suitable for AD	11
Reconfiguring supply chain: consumers becoming prosumers, ownership?	11
Software requirements and infrastructure in redistributed environment. How is it accessed?	11
Liability and IPR: traceability, certification	8
Material supply chain – how structured and delivered?	8
"Facebook problem" who owns/shares design in re-distributed 3DP hubs?	8

3.3 The Development of Selected Research Topics to Identify Potential 3DP-RDM Feasibility Studies[3]

Following the outputs of the prioritisation process, participants were invited to join in groups of 4–5 people to explore one of the prioritised topics. This resulted in the creation of the eight groups listed in Table 2.

The eight groups were provided with a second template as shown in Fig. 3. Through following the steps in this template, members of the group learned about each others' research expertise and interests, before exploring what research could be conducted within the chosen topic. After generating some ideas about possible research needs and research questions, groups then chose three to explore in greater depth, considering how these could be addressed though feasibility studies. A final step was to decide which of these three feasibility studies was most important.

[3] Full results can be found here: https://capturingthevalue.wordpress.com/2015/02/13/3dp-rdm-scoping-workshop-discussion-activity-2-outputs/.

Table 2. The eight groups formed for the second discussion activity

Group(s)	Research topic
1	Material supply chain
2	Standards + Compatibility + Regulation + Certification
3	Reconfiguring supply chain: will consumers become prosumers?
4	Software and conceptual infrastructure
5, 6	How will value be created and captured in 3DP-RDM economy?
7	Who owns/shares designs in 3DP-RDM hubs?
8	Business models

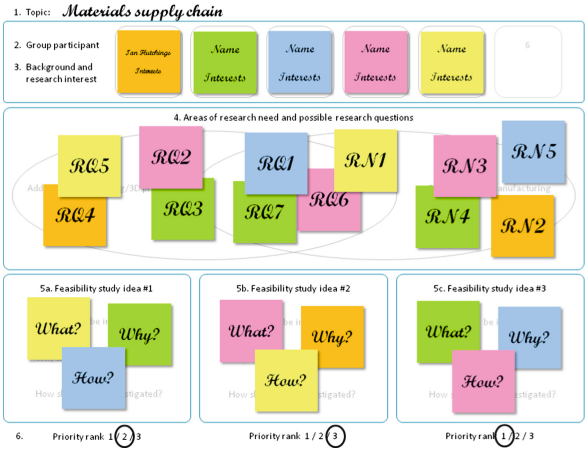

Fig. 3. Template used to discuss selected research topic and identify potential feasibility studies

The results of this second discussion activity provided the network with insights into the types of research questions and needs within the topic, and possible ways for researching the topic through feasibility studies. Example data is provided in Table 3.

Table 3. Summary of outputs from group 1 that explored the material supply chain

Areas of possible research	Feasibility study #1
• Dual sourcing of materials essential for robust process/business model • Security of supply • Effect of significant increase in demand on existing raw material supply chain • Exploration of new, cheaper sources of feedstock (currently very restricted) • Localised, small-scale production of feedstock • Local recycling of materials 'in-process' as feedstock for 3DP	• What should be investigated? Analyse existing feedstock supply chain: who, where, how, why? • Why should it be investigated? To inform: policy, investment. To identify: weaknesses, security issues, opportunity • How should it be investigated? Create example situations and interview stakeholders: 3DP user, material suppliers, end product OEM, regulators, manufacturing process experts

4 Feasibility Study Competition

An open call for feasibility study funding was announced at the scoping workshop as well as through the network blog and EPSRC website. The call invited proposals for feasibility studies investigating 3DP-RDM. A total of 34 proposals were received in response to this call. Following an initial screening process and indicative marking by a three person review panel, a shortlist of 9 proposals was created. This shortlist was then scored using the ten opportunity and feasibility criteria in Table 4. This scoring system was developed based on guidance from on the use of anchoring statements to drive consistency [10], the criteria used by EPSRC to select projects, with additional criteria specific to the nature of the 3DP-RDM feasibility study. In addition, due to some conflicts of interest that were identified during the indicative marking stage, the panel

Table 4. Selection criteria for feasibility studies

	0	3	6	9	12
Strategic importance	No link to explicitly identified issue		Some linkages but some supposition		Clear linkage to issue identified by policy documents
Future potential/impact	Unclear/absent potential impact		Some evidence of impact, but needs strengthening		Clear potential impact, and articulation of how this might be delivered
Synergy opportunities	Isolated research, no obvious linkages		Some potential synergy, but requires elaboration		Very clear engagement/complementarity with other projects
Learning potential	Weak/not discussed		Some, but benefit to network not clear		Clear learning for team and network
Timing and relevance	Low importance for being conducted now		Moderate importance for being conducted now		High importance for being conducted now
Quality	Vague, incomplete plan		Core elements of plan but some gaps		Complete plan: Clear aim, method, outputs
Applicant's domain expertise	Not relevant and/or not demonstrated		Some relevance but may need partner		Highly relevant and demonstrated
Alignment with applicant's existing research	No connection		Some alignment but extends beyond core area		Builds directly upon established high quality research
Resources	No appropriate researchers; justification unclear		Resources appropriate but not clear if available		Appropriate, named researcher available on start-date and for duration of project
Management	No detail on management		Basic management plan but some gaps		Clear management process and responsibilities

was increased to four reviewers to ensure that all applications were scored by at least three reviewers.
Following this review process four studies were selected for funding:

- *Investigating the Impact of CAD Data Transfer Standards for 3DP-RDM*
- *OPTIMOS PRIME: Organising Production Technology Into MOst Responsive States – 3D PRInt Machine Enabled Networks*
- *The enabling role of 3DP in redistributed manufacturing: A total cost model*
- *Redistributing Material Supply Chains for 3D printing*.

5 Conclusions

The interaction between 3D printing and the re-distribution of manufacturing is a complex one and has been identified as requiring further investigation. The four studies being funded by the 3DP-RDM network cover economic modelling, production systems, materials, supply chains, software and standards. Their selection ensures a balanced portfolio of projects and establishes a platform on which the 3DP-RDM research agenda can grow.

This paper has provided a detailed description of the process for generating and selecting feasibility studies in an emerging field of enquiry. It has demonstrated how the use of structured templates at a scoping workshop enables multiple disciplines to collaborate and synthesise their ideas. Customising these templates allows this process to be replicated in other academic domains in order to generate new research ideas, concepts and projects.

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