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STRATEGIC OPPORTUNITIES FOR PRODUCT-AGNOSTIC REMANUFACTURING

Original Submission to ISL 2021 Special Issue in IJLM

ABSTRACT

Purpose

There is now much emphasis in both research and practice on the principles of circular economies. In this paper we examine remanufacturing as a key enabler of circular practices and propose the concept of 'Product-Agnostic Manufacturing' (PAR). We differentiate PAR from many traditional approaches to remanufacturing by virtue of its treatment of product variety. Most existing approaches to remanufacturing feature low variety and standardization; we instead suggest that the exploitation of flexibilities in both operations and supply chains leads to new competitive strategies for firms to exploit.

Design/methodology/approach

This is a conceptual study that builds on a thorough exploration of contemporary remanufacturing literature in the development of the new PAR concept.

Findings

Through our literature review we show that there are a range of benefits, challenges, and critical success factors that underpin the remanufacturing concept. Building on this understanding and bridging literatures in operations flexibility and supply chain design we provide a detailed discussion on the nature of PAR and develop an agenda for future research.

Originality

Whilst there has been much literature on remanufacturing, there is a general tendency to treat supply chain and remanufacturing operations quite distinctly in individual articles. Additionally there has been little consideration of multi-product remanufacturing, and for the limited studies where this is done, the emphasis is typically on problem avoidance. This study aims to provide a detailed insight into the developed PAR concept, showing how the remanufacture of a wide range of product varieties may be achieved through flexible operations and supply chain design.

1. INTRODUCTION

Companies that do not engage with circular economy practices not only risk damaging the environment, but are also missing out on significant opportunities within their market too. A recent survey (Holm *et al.*, 2021) highlights that 72% of customers want more durable products, 70% want to maintain and repair their possessions, and once used, more people (69%) want to give products away for others to use rather than to simply recycle (64%). There is much evidence that firms are increasingly transitioning to Circular Economy principles. A review by Calzolari *et al.* (2021) examined a sample of large European multi-nationals, finding a progression from 1.5% identifying themselves as engaged in CE in 2015 to 50% in 2018. In small and medium-sized enterprises the EU uptake is higher; a large 2016 survey highlighted that 73% of the sampled firms undertook *some* circular-related activity (Katz-Gerro and López Sintas, 2019), mainly around recycling or material recovery. Given that circular economy activities such as remanufacturing can both lower costs and legitimately heighten environmental perceptions of a company, there is much merit in considering the circular economy as part of an overall strategy for the firm.

In traditional linear consumption models there is a pattern that depletes natural resources and pollutes the environment (Masi *et al.*, 2017). Circular economies aim to balance economic prosperity with environmental strain and resource depletion. To break this "take-make-consume-dispose" pattern, circular economies seek to minimise resource consumption by re-circulating used resources back into the supply chain (Winans *et al.*, 2017). Once products have reached their end-of-life, firms can either pay for their disposal, or retain part of their value by reintegrating them in their supply chain through circular economies. Remanufacturing represents a critical component of the circular economy, with significant benefits for economic, environmental, and social aspects of sustainability (Del Giudice *et al.*, 2021). Through remanufacturing resources are conserved, value is retained in products (Thierry *et al.*, 1995), landfill is lessened, and opportunities are created for increases in skilled employment (Laubinger *et al.*, 2020).

Commercial emphasis on remanufacturing has varied over the years. In the aftermath of World War 2 a shortage of components obligated some automotive industries to perform remanufacturing out of necessity; however post-war the benefits of a remanufacturing approach led to other thriving remanufacturing industries (Lieder and Rashid, 2016). Today, many firms are adopting the principles of remanufacturing within their supply chains. For example, Canon Inc has been remanufacturing multifunction devices since 1992; its imageRUNNER product currently includes 93.8% of reused parts (Canon, 2021). Similarly, Caterpillar offers over 7,600 replacement parts for its industrial equipment, typically at 60% of new-product pricing (Caterpillar, 2021). Additionally, Boeing recently secured contracts valued over \$500m to remanufacture Apache helicopters for three countries (Waldron, 2019).

Whilst conceptually attractive, remanufacturing is not a panacea for either profitability or sustainability. There is the potential for remanufacturing sales to cannibalise new product sales, particularly for industrial goods (Guide and Li, 2010). Reverse logistics activities, so critical for returning worn products for remanufacture, present their own environmental challenges (Guarnieri *et al.*, 2015), which will in-turn affect the environmental feasibility of remanufacturing. Hence in each of the three preceding examples, remanufacturing serves to complement existing manufacturing operations, with carefully controlled reverse supply chains that emphasise the individual firm's product offerings. Notably Canon does not remanufacture for HP equipment, Caterpillar isn't working on JCB plant kit, and Boeing does not remanufacture Airbus' aircraft. For these high-value specialist items an emphasis on a narrow product range that is specified by the OEM is sensible, where expert product manufacturing experience, access to specific technologies, and control of parts supply chains provides the fundamental building blocks for a competitive circular endeavour.

However, whilst this is often the prevailing approach to remanufacturing, it need not be the only one. Post-consumer closed-loops place remanufacturing as a key activity of the original supplier, but other (potentially better) opportunities for value creation may be feasible (Wells and Seitz, 2005). Indeed, with appropriate capabilities in the production system and supply chain, we argue the opportunity exists for the establishment of product-agnostic remanufacturing facilities: general purpose operations that can remanufacture a wide range of products, potentially for multiple different OEMs.

In this paper we propose the concept of Product-Agnostic Remanufacturing (PAR) and examine some of the potential benefits of the approach. Traditionally specialism in remanufacturing facilities tends to support a centralised approach, whereby a small number of remanufacturing facilities serve a wide geographic region. In PAR, we show the potential for more locally distributed facilities, which may be able to counteract lost economies of scale with new economies of scope by virtue of the increased variety of products that are capable of being remanufactured. The aim of this paper is therefore to provide a detailed examination of the PAR concept, and to set out some research directions concerning strategic choices that may affect the value derived from remanufacturing.

This paper is structured as follows. In Section 2 we explain the approach taken in the execution of this work, demonstrating the development of this conceptual piece. Next in Section 3 we provide a detailed synthesis of pertinent circular economy and remanufacturing literature, with a comprehensive synthesis of the benefits, challenges, and critical success factors to consider. From these literature foundations this conceptual work proposes extensions to conventional approaches in remanufacturing, providing an overview of PAR in section 4 and pertinent directions for research in section 5. We conclude by discussing the key findings and contribution of our work in section 6.

2. METHODOLOGY

In this paper we propose the novel concept of PAR, as a logical extension of current concepts within remanufacturing research and practice. To achieve this outcome, we tackled the exploration and explanation of the PAR concept through the principles of theory synthesis (Jaakkola, 2020): unlike traditional literature reviews which explain the current state of knowledge within defined boundaries, we looked beyond to contemporary developments across wider operations and supply chain research and practice in developing conceptual extensions for remanufacturing. Such an approach allows the 'bridging' of related developments in other research fields, and then adapting and contextualising them for this work in remanufacturing. We articulate the main elements of this approach within Figure 1, highlighting the main topics and developments comprised in this research.

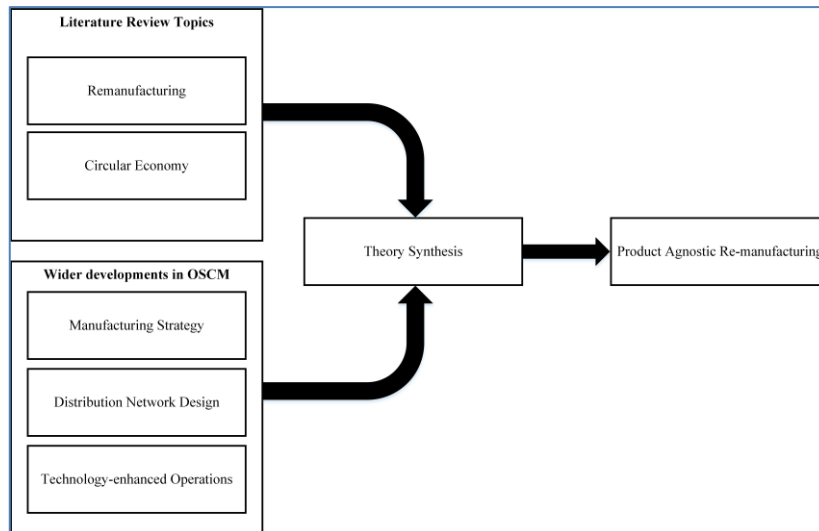


Figure 1: Development of PAR concept in this study

Our work was initially motivated by a single contemporary development: the application of Additive Manufacturing (3D printing) in the repair of broken artifacts, undertaken by individual ‘makers’ in Fab-lab settings. Though there is scant research in this area, such facilities have the potential to enable a wide range of repair operations (Hielscher and Jaeger-Erben, 2021) but in localised facilities. This is possible because of the flexibility of 3D printers to make a wide range of products without restrictive setups and punitive cost penalties for single-unit production. For the manufacture of *new* parts (i.e. not repair or remanufacturing), such technologies are already being promoted as decentralising manufacturing (Holmström and Partanen, 2014), enabling hyper-local production (Demir *et al.*, 2021), and providing opportunities for production outsourcing (Hedenstierna *et al.*, 2019). Many of these characteristics may also be suitable for *used* parts in their remanufacture, for which Additive Manufacturing technologies are beginning to be employed (Despeisse *et al.*, 2017).

Though we were not particularly interested in Additive Manufacturing technologies as the focus for our work, the potential for such general-purpose repair facilities was of much interest to us. Within manufacturing strategy literature there is a long-established linkage between flexibility in operations and the enablement of general job-shop operations (Hayes and Wheelwright, 1984), though comparatively little emphasis has been placed on this in remanufacturing. With such developments as Additive Manufacturing offering increased flexibility, we were curious as to whether existing academic research had considered these from the circular economy perspective of remanufacturing, and how such product-agnostic approaches would be understood from a supply chain perspective.

We undertook a detailed review of the literature, adopting a narrative approach that was initially informed by keyword searches, conjoining five themes with a selection of pertinent attributes (

). We then employed snowballing strategies to follow-up references and to support a rich understanding of contemporary approaches in remanufacturing literature. By using a combination of Google Scholar and EBSCO Business Source Premier, we were able to

consider a wide range of journals, conference papers, and trade articles that met our aim of understanding both research and industrial practices in remanufacturing.

		Attributes Explored					
		Definition	Characteristics	Components	Challenges	Benefits	Critical Success Factors
Theme	Remanufacturing	x	x	x	x	x	x
	Circular Economy	x	x	x	x	x	x
	Reverse Logistics	x	x	x			x
	Reconditioning	x	x				
	Refurbishment	x	x				

Table 1: Keyword search terms used to inform narrative literature review

3. CONCEPTUAL REVIEW

In this section a detailed investigation of the literature is undertaken to support the later development of the PAR concept and associated research agenda. We provide a thorough overview on the contribution remanufacturing plays in the circular economy, together with an examination of the benefits, challenges, and identified critical success factors pertinent to a successful remanufacturing strategy.

3.1 Principles of Remanufacturing

Remanufacturing is an important part of the circular economy, though its definition has evolved as research has progressed and matured. Whilst there is no consensus on a single explanation, remanufacturing definitions generally fall into one of three categories:

1. Value-retained: A description of the processes and activities involved in remanufacturing, highlighting the value retained in the product (Ferrer and Whybark, 2000, Jiang *et al.*, 2016).
2. Like-new: A description of a process with multiple steps (to varying degrees of detail) which brings an end-of-life product back to like-new condition (Haynsworth and Lyons, 1987, Bernard, 2011).
3. As-new: A description of a process with multiple steps to bring a product back to an as-new condition with corresponding warranty (Ijomah *et al.*, 2007, Sitcharangsie *et al.*, 2019).

Though highlighting the value retained during the remanufacturing process helps distinguish it from alternatives such as recycling, the definition leaves much room for interpretation. This can be problematic, as the activities carried out in the process largely overlap with other alternatives such as reconditioning and refurbishment, and even some activities from forward supply chains. The like-new category was introduced by Haynsworth and Lyons (1987) but was considered ambiguous as it did not differentiate between reconditioning, repairs, and remanufacturing, leading to problems for both researchers and practitioners (Ijomah *et al.*, 2004). Subsequently various authors have suggested a third definition, where remanufacturing is the process of restoring a used product to the OEM's

original performance specifications (or even better) as perceived by the customer, and reflecting this in a product warranty that is at least equal to the warranty on its newly manufactured equivalent. In other words, the remanufactured product is at least as good as the new version. For the purposes of the current study, we consider remanufacturing to be the process that restores an end-of-life product to an as-new condition, with corresponding warranty restoration.

Many researchers have explored the nature of remanufacturing to identify the unique characteristics that distinguish it from linear manufacturing, though notably from different perspectives. For example, from a high-level strategic perspective Subramoniam *et al.* (2009) splits remanufacturing into product strategic planning process, physical distribution structures, plant location and production systems, and cooperation among remanufacturing supply chains. Bringing more attention to supply chain issues, a nuanced approach is shown by Vasudevan *et al.* (2012), who defines the key elements in remanufacturing as product acquisition management, framework for reverse logistics, reverse logistics collection models, basic remanufacturing product development, demand and supply for remanufactured product, and remanufacturing decisions. Focusing more on individual factory operations, Sitcharangsie *et al.* (2019) define key activities in remanufacturing as core acquisition, disassembly, cleaning, inspection, reworking, reassembly, and testing. These examples serve to highlight remanufacturing can be considered from a multitude of perspectives, and it is important to consider both strategic and operational considerations. A helpful article by Barquet *et al.* (2013) takes a systems perspective to remanufacturing, bridging both operations and supply chain considerations to define the remanufacturing system as a set of elements and sub-elements:

1. Remanufacturable product design
2. Reverse supply chain
 1. Acquisition/supplier relationships
 2. Reverse logistics
3. Flow of information within the system
4. Remanufacturing knowledge/skills of labour
5. Remanufacturing operations
6. Marketing of remanufactured products

Whilst there is much variation on the individual interpretations of remanufacturing, some general conclusions can be drawn. First, from the *product* perspective, just as 'design for manufacturing' principles are well established for manufacturing, much importance is also placed upon the design of products so that they can be effectively remanufactured. Secondly, in terms of *processes* and their operations, it is apparent that remanufacturing operations share many commonalities with conventional operations in terms of their transformative nature. The difference being manufacturing tends to use new materials as inputs, whereas remanufacturing will also use recovered materials (products). It is therefore unsurprising to observe many concepts (e.g. plant location, planning etc) shared between the two. Finally, it is evident that whilst manufacturing and remanufacturing are both reliant on effective management of the *supply chain*, remanufacturing research places much emphasis on the reverse supply chain and the challenges inherent in this.

3.2 Remanufacturing in the Circular Economy

The Circular Economy is based on three principles: waste elimination, circulation of products and materials (at their highest value), and nature regeneration (Ellen MacArthur Foundation, 2022). Circular economies employ various strategies to maintain products in a viable condition for as long as possible, for which remanufacturing is but one in a series of 'R' strategies). Potting *et al.* (2017) identify that these strategies may be divided into three categories:

1. Smarter product use and manufacture (R₀ - Refuse, R₁ - Rethink, R₂ - Reduce)
2. Lifespan extension of products (R₃ - Reuse, R₄ - Repair, R₅ - Refurbish, R₆ - Remanufacture, R₇ - Repurpose)
3. Useful application of materials (R₈ - Recycle, R₉ - Recover)

Within this framework the lower the R-value, the higher the degree of circularity and thus lessened environmental pressure. Category 1 strategies actively avoid consumption, category 2 strategies aim to retain value in products for as long as possible, and category 3 aims to do the best with materials at end-of-life.

It is notable that within the lifespan extension category there is much variation in terminologies used for the 'R strategy'. For example, some literature considers 'reconditioning' synonymous with refurbishment, whereas for others it implies a stronger link with remanufacturing. As a result, despite much work on definitions, there remains much confusion over the distinction between remanufacturing and other alternatives within lifespan extension such as refurbishment, reconditioning, and repairs. To clarify understandings in this paper, we draw upon Ferrer and Whybark (2000) who distinguish remanufacturing from recovery, saying that recovery singles out parts for reuse and sends the rest for recycling, whereas remanufacturing restores the returned product to like-new status. Additionally, Ijomah *et al.* (2004) explored the difference between remanufacturing, reconditioning, and repairs in terms of work content, performance, and warranty. According to them, reconditioning brings a returned product back to "adequate" working condition (not as good as "like-new" condition) without promising a like-new warranty. Repairs only recover specified defects in a returned product, often resulting in the lowest level of quality of the alternatives, with only a partial warranty that is specific to the repaired component. Elaborating on this, Gharfalkar *et al.* (2016) developed a hierarchy of multiple reuse options including reuse without any processing, repairing, reconditioning, refurbishing, and remanufacturing. From a manufacturing perspective, it is notable that reuse is the only option in the hierarchy that does not require any manufacturing operations or processing. Repairs require processing, but only focus on specified problems in a product or component, and offer no warranty, or warranty only on the repaired components of the product. Reconditioning brings back a product to adequate working condition, which is generally inferior to a like-new condition. Refurbishment is most like remanufacturing in that it restores a product to like-new condition or close to it, but there is no evidence that refurbished products reflect this in their warranty. Thus, whilst there are many approaches that can be taken in the circular economy, process capabilities in remanufacturing facilities represent an important underpinning capability, as it requires the highest investment in energy and work content to achieve the highest level of quality and performance of the alternatives (Gharfalkar *et al.*, 2016).

3.3 Benefits and challenges of remanufacturing

When remanufacturing is done successfully, it can offer numerous economic, social, and environmental benefits (Steinhilper, 2001, Cohen, 2010, Kalverkamp, 2018).

Economically, these benefits include cost savings, mostly in terms of cost of raw materials and cycle cost. Cost saving potential depends on the industry, product, and process, but savings can range from 20% to 80% (Ijomah *et al.*, 2007). Consequentially, there is a potential for increased profits (Ferrer and Whybark, 2000, Su and Xu, 2014), and increased sales by offering remanufactured products to different target audiences (Steinhilper, 2001). Consequentially, there is a potential for increased profits (Ferrer and Whybark, 2000, Su and Xu, 2014), and increased sales by offering remanufactured products to different target audiences (Steinhilper, 2001)

Social benefits are less commonly discussed in literature, but are mostly related to the creation of local jobs, as labour is required to re-process returned products (Steinhilper,

2001, Matsumoto *et al.*, 2016). This increases the awareness of remanufacturing within the area where products are returned. Increased awareness and use of remanufacturing services, in turn, increase demand for skilled labour, providing local opportunities for employment.

The environmental benefits of remanufacturing are most frequently discussed in literature. Some authors state generic environmental benefits (Steinhilper, 2001, Zwolinski and Brissaud, 2008), whereas others focus on more specific environmental benefits such as energy savings, reduced emissions (Deng *et al.*, 2018), reduced air pollution (Jiang *et al.*, 2016), as well as reductions in raw material usage (Ijomah *et al.*, 2007, Jiang *et al.*, 2016, Wang *et al.*, 2019).

Though remanufacturing can certainly be of benefit, it is not always as effective as it may seem. For instance, though emissions are reduced on a factory level due to reuse of materials, emissions generated through reverse logistics may actually increase. These types of nuances have not been researched much, and can be ignored when authors emphasize the benefits of remanufacturing. However, whilst there is increasing research and commercial uptake for remanufacturing, there remain a multitude of challenges that face remanufacturers. Many of the issues traverse the overall supply chain, and so in this section we categorize them broadly in-line with the key activities identified within the Supply Chain Operations Reference (SCOR) model (APICS, 2021). We summarise the key challenges and notable texts in Table 2.

SCOR Category	Challenge	Notable texts
Plan <i>developing plans to operate the supply chain</i>	Balancing returned supply and demand	Subramoniam <i>et al.</i> (2009), Su and Xu (2014)
	Identifying markets without cannibalising	Thierry <i>et al.</i> , (1995)
Source <i>ordering, delivery, receipt and transfer of raw material items, subassemblies, products or services.</i>	Uncertainty in returned product type supply	Ijomah <i>et al.</i> (2007), Martin and Craighead (2010) Goodall <i>et al.</i> (2019)
	Uncertainty in returned product quality	Guide <i>et al.</i> (2003), Martin and Craighead (2010), Barquet <i>et al.</i> (2013), Su and Xu (2014), Kurilova-Palisaitiene <i>et al.</i> (2017), Goodall <i>et al.</i> (2019), Liu <i>et al.</i> (2020)
	Uncertainty in returned product volume	Goodall <i>et al.</i> (2019); Guide <i>et al.</i> (2003), Junior and Filho (2012)
	Uncertainty in returned product timing	Su and Xu (2014), Sitcharangsie <i>et al.</i> (2019)
Make <i>conversion of materials through chemical processing, maintenance, repair, overhaul, recycling, refurbishment, manufacturing and other common types of material-conversion processes.</i>	Uncertainty in technological generation	Ijomah <i>et al.</i> (2007), Martin and Craighead (2010), Kurilova-Palisaitiene <i>et al.</i> (2017)
	Difficulty in matching materials	Junior and Filho (2012), Sitcharangsie <i>et al.</i> (2019)
	Lack of technical skills	Ijomah <i>et al.</i> (2007)
	Uncertainties in production yields	Schulz and Ferretti (2011), Hosoda <i>et al.</i> (2015)
	Optimal facility design	(Tang and Teunter, 2006, Teunter <i>et al.</i> , 2008)
Deliver <i>creation, maintenance and fulfilment of customer orders</i>	Identifying strategies to get remanufactured products into supply chains	Abbey <i>et al.</i> (2019)
	Locating adequate warehousing and remanufacturing facilities	Marín and Pelegrín (1998), Lu and Bostel (2007), Tagaras and Zikopoulos (2008)
Return <i>activities undertaken in the reverse flow of goods</i>	Loss of efficiency	Liu <i>et al.</i> (2020)
	Design of reverse supply chains	Tang and Naim (2004), Subramoniam <i>et al.</i> (2009), Junior and Filho (2012), Dominguez <i>et al.</i> (2021)
	Unique / stochastic process routings	Ijomah <i>et al.</i> (2007), Kurilova-Palisaitiene <i>et al.</i> (2017), Sitcharangsie <i>et al.</i> (2019)
Enable <i>activities associated with the management of the supply chain, including regulation</i>	Legislation	Ijomah <i>et al.</i> (2007), Kurilova-Palisaitiene <i>et al.</i> (2017)
	Intellectual property rights	Ijomah <i>et al.</i> (2007), Martin and Craighead (2010)
	Restrictive policies from OEMs	Ijomah <i>et al.</i> (2007)

Table 2: Key challenges in contemporary remanufacturing operations

3.4 Critical success factors for remanufacturing

The concept of Critical Success Factors (CSFs) was introduced by Daniel (1961) and describes a limited number of factors that determine the level of competitive performance of an organisation (Leidecker and Bruno, 1984). Popularised by Rockart (1979) to strategically plan information systems and technologies within organisations, CSFs have gained much interest in various domains, with some recent attention being paid to circular economies (e.g. Bhatia and Kumar Srivastava (2019), Schenkel *et al.* (2015)) and remanufacturing (e.g. Ansari *et al.*, 2019, Singhal *et al.*, 2020).

The preceding sections have shown that there are many potential benefits and challenges of remanufacturing, but simply understanding these will not enable successful remanufacturing. In this section we therefore turn to the CSF concept, which can help a remanufacturer achieve the benefits whilst navigating the challenges of remanufacturing. Focusing on the operations of a remanufacturing system identified by Barquet *et al.* (2013), in Table 3 we provide a synthesis of the principal remanufacturing literature that has explicitly considered critical success factors in the context of remanufacturing, circular economies, and/or reverse logistics. It is important to note, however, that it is not necessary for a remanufacturer to have all these critical success factors in place. Rather, a subset should be achieved that help a remanufacturer circumvent specific (potential) issues.

	Critical Success Factor	Literature Observations	Author										
			Ansari <i>et al.</i> (2019)	Bhatia and Kumar Srivastava (2019)	Chakraborty <i>et al.</i> (2017)	Chaowanapong <i>et al.</i> (2017)	Deng <i>et al.</i> (2018)	Julianelli <i>et al.</i> (2020)	Luthra and Mangla (2018)	Luthra <i>et al.</i> (2015)	Mangla <i>et al.</i> (2016)	Matsumoto <i>et al.</i> (2016)	Singhal <i>et al.</i> (2020)
Remanufacturable Product Design	Design for remanufacture (DFR)	When products or components are designed with remanufacturing in mind, remanufacturing becomes more feasible. DFR is often concerned with decoupling points and a parts-based design.	x	x	x	x	x	x		x		x	x
	Product maturity	Design stability is crucial for remanufactured products as changes in design lead to incompatibility for remanufacturing activities. Mature products are usually more stable in design and technology.				x							

	extended warranty	remanufactured products by offering extended warranty helps persuade hesitant potential consumers.												
	Separate market for the new and remanufactured products	Offering remanufactured products to different markets than newly manufactured products helps prevent cannibalisation.			x									

Table 3: Identified Critical Success Factors for Remanufacturing

3.5 Distribution network design for remanufacturing

Literature on closed-loop supply chains seldom focuses on specific locational issues, however these have a large effect on supply chain cost and service levels (Chopra, 2003, Firoozi *et al.*, 2020). This, combined with the recognition that supply chains are very complex, means that distribution network design is a complicated topic. The effective management of distribution network design is hence critical to an organisation’s logistical and operational management (Jayaraman 1998). There is no one-size-fits-all distribution network, and designs need to change over time (Drickhamer, 2006).

Distribution network design affects both service levels in multiple different areas, including lead time, variety in product, customer experience, order visibility, and returnability of the product. Costs are in part determined by distribution network design though the cost of holding inventories, transportation, facilities and handling, information (Chopra, 2003). An important topic in this context is the level of centralisation (or decentralisation) of inventories. For traditional manufacturing this usually refers to raw materials, components, and finished goods. In remanufacturing this is also extended to include inventories of used products for processing too. Generally, an organisation can choose to either centralise inventories to enjoy the benefits of economies of scale at the expense of service levels and logistics costs, or it can opt for decentralised inventories where service levels remain high at lower logistics cost, but negating the benefits of economies of scale.

Of course, there are trade-offs in both strategies that focus centralised inventories, as well as decentralised inventories. Centralising inventories can be beneficial towards the holding cost of inventory due to the square root law (Maister, 1976), whereby the inventories required in several decentralised warehouses, is equal to the inventories required by one central warehouse, multiplied by the square root of the number of decentralised warehouses. Centralised inventories have a significant cost advantage over decentralised inventories (Oeser and Romano, 2016, Gregersen and Hansen, 2018). Additionally, in manufacturing, centralising inventories also allows for economies of scale to be reached, as greater volumes can be produced on fewer sites (Christopher, 2016), and the potential of reduced shortage costs (Oeser and Romano, 2016) (Oeser and Romano 2016). However, centralisation of inventories also has drawbacks. Firstly, though production and inventory costs may be lower, transportation costs will most likely increase, as products must travel longer distances (Christopher, 2016, Oeser and Romano, 2016). Additionally, to achieve economies of scale, flexibility may be lost (Christopher, 2016). The pipelines also tend to be longer, resulting in slower response times to customer demand, and hence lower service levels (Chopra, 2003, Christopher, 2016). These are all important considerations for remanufacturers to consider when formulating their own network designs.

4. PRODUCT-AGNOSTIC REMANUFACTURING

In defining remanufacturing, emphasis has been placed on the eventual product outcome of the remanufacturing process, and in Section 3.1 this was shown to be 'value-retained', 'like-new', or 'as-new'. To achieve these outcomes there is a need for appropriate coordination of supply chains and effective remanufacturing operations to achieve required product transformations. From the supply chain perspective there has been much emphasis on issues such as product recovery (Seitz, 2007), facility location (Deveci *et al.*, 2021), and overall supply chain design (Tang and Naim, 2004). Likewise, in remanufacturing operations there is a plethora of research around production-related issues such as quality assessment (Ferguson *et al.*, 2009), scheduling (Guide *et al.*, 1997), and forecasting of demand and returned products (Wei *et al.*, 2015).

There are two notable observations in the literature. First, there is a tendency to treat the supply chain and remanufacturing operations quite distinctly in individual articles. Whilst such approaches allow focused consideration of relevant aspects of remanufacturing, the more holistic approach is necessary to offer a fuller (and arguably more effective) approach to remanufacturing. Secondly, there is often little explicit focus on the nature of products to be remanufactured, or the specific processes by which this is done. Many quantitative evaluations of remanufacturing focus on a generic product for the purposes of modelling operations (e.g. Shi *et al.*, 2011, Zanoni *et al.*, 2012). Interestingly, there has been little consideration of multi-product remanufacturing (Rizova *et al.*, 2020), and for the limited studies where this is done, approaches typically focus on operating distinctly different lines for different products, or looking for commonalities in product families.

There are many obvious reasons for focusing on a very limited number of products in both manufacturing and remanufacturing operations. Classic strategy literature has long forewarned the issues of losing focus in manufacturing (Skinner, 1974), and has shown that introducing product variety introduces complexity (Hu *et al.*, 2008), forecasting uncertainties (Wan and Sanders, 2017) and negatively affects performance (Zipkin, 1995, MacDuffie *et al.*, 1996). The impact of variety in remanufacturing is likely to be felt even more severely. In remanufacturing, where variable quality of returned products affects inputs, this further complicates operations and thus attracts increased disincentives for multi-product remanufacturing. As such, of the texts that discuss variety in remanufacturing, many discourage it (Hu *et al.*, 2011, Huang and Su, 2013), or advocate strategies that promote standardization in component modules such as Product Family Design (Wu *et al.*, 2017) and modularity (Krikke *et al.*, 2004) for circular supply chains.

In this paper we do not argue against the benefits of product variety reduction / standardization in remanufacturing, which will promote flow, efficiencies, and ultimately competitiveness in the market. As in conventional manufacturing, firms operating in these circumstances enjoy the many benefits of repetitive production. However, just as not all manufacturing is standardized and designed around high-volume line-based production, there are many other opportunities arising for remanufacturing in higher variety situations. Instead, we suggest that there are additional untapped opportunities for both research and practice in emphasising a more product-agnostic approach to remanufacturing, where facilities are not constrained by individualistic approaches to the remanufacture of products. Ashby's Law of Requisite Variety (Ashby, 1961) identifies that firms need a selection of responses to that are (at a minimum) as nuanced as the challenges it faces. In situations of product variety, this means production systems must have the capability to produce at least as many product variants as are offered to the customer (Eyers *et al.*, 2021). We contend that remanufacturing research and practice therefore need not be constrained to narrow product ranges; simply there is a need to carefully design and extend the capabilities of remanufacturing systems. Specifically, we introduce PAR as a means by which firms can competitively engage in remanufacturing very high varieties of products, leveraging economies of scope to counteract lost economies of scale. In-line with the preceding text, we now discuss the characteristics of PAR from both the remanufacturing

operations perspective, and that of the supply chain since both are essential in supporting an effective remanufacturing strategy.

4.1 PRODUCT-AGNOSTIC REMANUFACTURING OPERATIONS

Literature suggests that remanufacturing operations are besieged by uncertainty concerning the volume and quality of returned products. Once returned from customers, each product will be evaluated in terms of whether it can be remanufactured; those products deemed infeasible for remanufacture are sent for disposal or recycling. Thereafter, every distinct product effectively has variants in terms of its returned quality (i.e. specific defects). As the range of products increases, the associated quality variants therefore increase the variety challenge further, effectively by extending the range required for mix flexibility (Bateman, 1999). Whilst conventional remanufacturing strategies attempt to constrain this variety, in PAR this may lead to opportunities for remanufacturers.

Established wisdom in manufacturing strategy has identified that to deal with increasing product variety firms should look to flexibility competencies and capabilities in both individual processes and the overall manufacturing system (Slack, 1987, Jain *et al.*, 2013). Whilst in principle flexibility should not result in any performance degradation (Upton, 1994), the fundamental tenet of the product-process mix suggests otherwise (Wheelwright, 1984). Highly flexible processes offer firms the ability to deal with change (e.g. variety), but this comes at a loss of scale economies. Whilst there has been extensive dialogue over the existence of trade-offs in operations (Sarmiento *et al.*, 2018), there is reasonable agreement that intelligent choices and the application of technology and manufacturing practices can significantly abate (albeit not always eliminate) these (New, 1992, Skinner, 1992)

In PAR we suggest that the application of appropriate process technologies within appropriate remanufacturing systems can enable remanufacturing without excessive concern as to the nature of the product – i.e. an agnostic approach. For example, there is much emphasis in recent work on the opportunities for Additive Manufacturing / 3D printing to be transformative in manufacturing operations (D'Aveni, 2015, Huang *et al.*, 2021), in terms of being able to manufacture products with otherwise-impossible material properties (Cheng *et al.*, 2021), in the production of on-demand spare parts to eliminate costly inventories (Holmström *et al.*, 2010), and also in terms of the wide variety of products that can be made (Berman, 2012, Rindfleisch *et al.*, 2017).

Whilst the media contention that these technologies can produce *anything* has largely been dismissed through research, there is general consensus that these technologies are able to competitively achieve a wide variety of product outputs. Several academic studies have extended this to formally examine Additive Manufacturing in terms of flexibility (e.g. Evers *et al.*, 2018). This has led to questions over whether Additive Manufacturing overcomes traditional manufacturing trade-offs (Helkiö and Tenhiälä, 2013), with recent empirical work providing support for this proposition in the case of existing products, but not where new research and development is required to print the part (Evers *et al.*, 2021). As a process technology which has already been demonstrated as offering much potential for spare parts production *and* to offer flexibility for high volume production within the manufacturing operation, there is good reason to suggest such technologies may be instrumental in PAR, and in overcoming trade-offs that affect remanufacturing systems. For example, whilst conventional remanufacturing operations typically focus on narrow product ranges to support focus in production and minimise setups, whilst Additive Manufacturing can accommodate a much broader range of products without penalty. Similarly, modern Additive Manufacturing systems are increasingly capable of a wide range of production volumes (Huang *et al.*, 2021), which is particularly important in remanufacturing where forecasting returns can be challenging (Goltsos *et al.*, 2019).

Whilst Additive Manufacturing seemingly offers many potential benefits, this does not, however, discount the potential of some very traditional technologies for which whilst there is little research on their flexibility, there is good reason to suggest they might enjoy high degrees. Whilst Additive Manufacturing might be driving Industry 4.0, in the hands of a skilled operator, a single industrial sewing machine (an Industry 1.0 technology) can enable the remanufacture of an enormous range of fabric-based products: furniture upholstery (home, office, automotive), bedding, clothing, soft toys, canvas tents etc. Flexibility is one of the critical success factors of remanufacturing (Table 3), and we acknowledge that there are many other similar technologies which, by virtue of their flexibility, might serve to support PAR. Underlying the successful enablement of these will be other resources of the manufacturing system, for which careful coordination will be needed to ensure flexibility within the whole system (Slack, 1987). Using Additive Manufacturing as an example; whilst the machines are well acknowledged to offer process flexibility, there is also the need for flexibility in labour and in other related process activities to ensure an overall flexible response (Eyers *et al.*, 2018). In PAR there is a need for flexibility in the way operations are configured, so as to accommodate the challenges of increased product range. One growing area of application for repair operations at the community level exists within 'MakerSpaces' where a multiskilled people work together using general-purpose tools in a public environment (Campos and Cipolla, 2021, Hielscher and Jaeger-Erben, 2021). Whilst such environments do not usually operate in a commercially competitive manner, they have been identified as effectively 'test beds' for piloting concepts before industrial upscaling (Prendeville *et al.*, 2017, Carrière *et al.*, 2020), though as-yet there remains scant research in this area.

4.2 PRODUCT-AGNOSTIC REMANUFACTURING SUPPLY CHAINS

In manufacturing that promotes high-volume, repetitive processes for a small range of products, emphasis is on scale and repeatability in operations; the same is true for remanufacturing. Remanufacturing supply chains are often dominated by large operations, which serve an extended geographical area. In such remanufacturing, the challenge is to recover failed products from a distributed network of customers, and return them to one (or a few) centralised facilities.

For PAR the economies of scale advantages are degraded by increased variety and a reliance on flexibility, but instead new economies of scope emerge in terms of the wider product range than can be accommodated in a single facility. Thus this increased product range supports opportunities for either continuing a centralised approach, or instead turning to decentralised remanufacturing. As noted in Section 3.5 centralization strategies minimise the number of facilities to be maintained, and for PAR could be feasible by virtue of the breadth of products remanufactured.

Alternatively, decentralized approaches are quite feasible in PAR, where localised remanufacturing facilities are located near the customer base, serving a comparatively small number of customers, but with a very wide range of products. As facility numbers increase, localised satisfaction of demand lowers transportation requirements (both inbound and outbound), potentially lessening overall transportation costs faced by the remanufacturer. By virtue of the range of products that PAR can address, there are also new opportunities for collaboration between remanufacturers. As indicated in the literature, operating multiple (remanufacturing) facilities often comes at great inventory and facility cost. However, in PAR, by allowing multiple organisations to utilise the same facility, total volumes are higher and fixed costs can be amortized over a greater number of products, resulting achievement economies of scale. Additionally, the presence of remanufacturing centres in multiple geographic locations in closer proximity to the customer (i.e. both demand of new products and supply of returned products) allows for these economies of

scales to be achieved whilst minimising the logistics costs associated with centralised inventories (Figure 2).

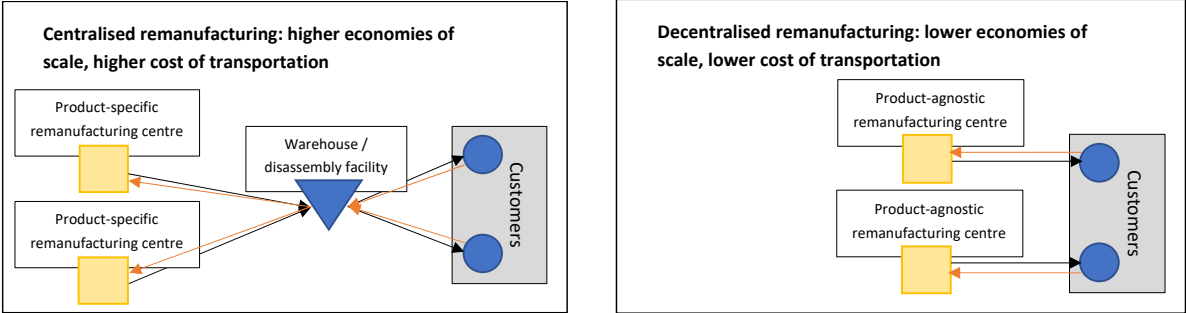


Figure 2: Comparing centralized remanufacturing with decentralized PAR

An interesting opportunity for decentralised remanufacturing is already emerging in the form of third-party logistics providers. These organisations often have extensive warehousing operations that are geographically dispersed, meaning that they are likely to be closer to the customer than a centralised remanufacturer. Larger companies such as DSV are already offering localised manufacturing services from their warehouses, and are extending this to remanufacturing operations too (DSV, 2022). For these types of organizations which work with a wide range of customers and have expertise in reverse logistics, the achievement PAR would offer an additional competitive offering to their range of services, supporting a productization of their overall service offering (Lahy *et al.*, 2018).

PAR also offers interesting opportunities within the sustainable circular economy. From a localisation of remanufacturing perspective, it offers a more equitable approach to managing waste by ensuring it is treated local to where it is produced. This promotes shorter, local supply chains which (in general) have been associated with improvements in efficiency, reliability, and robustness. More local remanufacturing also has the potential to raise awareness of remanufacturing, which is often identified as being very lacking in both consumer and industry mindsets.

The collaborations enabled by PAR also supports redistribution of power within the supply chain. Many OEMs exert influence and control over the remanufacture of their products, with examples previously shown in Section 1. This may be performed wholly in-house, or draw upon specialists in the supply chain for the remanufacture of specific component parts. This approach allows OEMs to control quality and pricing of their remanufactured offerings, maintaining both brand reputation and overall profit margins with product-specific remanufacturing operations. In some industries (e.g. printer cartridges, car gearboxes) there has been a weakening of this overall OEM control as independent firms set up their own product-specific remanufacturing operations. This independent establishment of facilities requires significant resource commitment and particularly for smaller remanufacturers, decentralised remanufacturing as displayed above is difficult to achieve, since volumes of returns will be low and stochastic in nature. Collaborating with companies offering similar products or services may lead to full utilisation of capacity in a PAR centre, allows these firms to both enjoy the benefits of decentralised remanufacturing (higher service levels, lower cost of transportation), as well as enjoy the benefits of centralised inventories (thus economies of scale).

A summary comparison of conventional and PAR remanufacturing is shown in Table 4.

	Conventional Remanufacturing	PAR Centralised	PAR Decentralised
Organization	Centralised	Centralised	Decentralised
Geography Served	Large	Lage	Small
Product Variety	Low	High	High
No. of customers Served	Low	Low-High	High
Return Distances	Longer	Longer	Shorter
Operations Configuration	Specialised, focused	Flexible technologies, reconfigurable resources	
CE Benefits	Efficiency in remanufacturing	Increases availability of remanufacturing capability to new and existing firms	

Table 4: A comparison of conventional and PAR remanufacturing

5. A RESEARCH AGENDA FOR PRODUCT-AGNOSTIC REMANUFACTURING

The defining characteristic of PAR, and what separates it from conventional strategies, is its opportunistic utilization of flexibility in both remanufacturing operations and associated supply chains. This allows a PAR facility to tackle a much-increased range of product variations (designed and quality-resultant) without significant degradation to operational efficiencies. As a result, there are a multitude of potential implementations possible in PAR – from small, high-tech hyper-local remanufacturing plants that employ City Logistics strategies (Savelsbergh and Van Woensel, 2016) to recover and reprocess failed products with an emphasis on responsiveness, through to large-scale centralised facilities serving broad geographies with an emphasis on efficiency. Likewise, it is plausible that a more nuanced strategy targeting specific industry groups can help achieve economies of scale, through the generation of economies of scope. This could be of particular interest for SMEs, or for smaller product groups within companies, as well as non-standard manufacturers who primarily offer services, rather than products. Furthermore, PAR facilities need not be for the sole use of an individual company; the use of a PAR centre creates the possibility for multiple companies to make use of the same remanufacturing resources.

At its most extreme interpretation PAR facilities theoretically have the potential to remanufacture any product returned with a viable state of quality. When compared to many current approaches in remanufacturing this could be considered rather fanciful, but already related examples can be drawn from commercial settings. In vehicle repair operations there are long-established business models for low variety (i.e. manufacturer-specific) and high-variety (independent, generic) repair shops. Local demand will affect the viability of the manufacturer-specific facilities; a large city might support a franchise of every major dealer, whereas more sparsely populated areas may only feature a selection of manufacturer. By contrast independent facilities that are capable of undertaking most work on most vehicles enjoy prevalence in all areas. Whilst many other types of repair shop have been in decline, some evidence of diversification into wide product ranges is also evident: for example TV repair shops often tackle general repairs on generic electronic devices, and many cobblers also now undertake jewellery repairs and key cutting. In PAR we identify that as process technologies become more flexible, the range of products may grow extensively. It has already been shown that Additive Manufacturing service bureaus are increasingly providing access to these flexible manufacturing technologies to produce new products (Rogers *et al.*, 2016, Chaudhuri *et al.*, 2019), and so we posit that it is quite feasible that such facilities could adapt to accommodate the remanufacture of products too.

There are, then, many possible ways to implement a PAR approach, many of which will be driven by either the individual strategy of a focal company, or the collective strategies of collaborative and cooperative companies within a market. Within Section 3.4 we have shown that in general there are a multitude of Critical Success Factors for remanufacturing, and it is reasonable to assume that many of these will apply in PAR, albeit to greater or lesser degrees. For example, designing for remanufacturing is likely to remain very relevant in all implementations of PAR, since this is likely to affect the ability of operations to reprocess returned items. By comparison, the standardisation of operations guidelines is likely to be less important within remanufacturing operations thanks to increased flexibility capabilities, but will remain important within the co-ordination of the supply chain. There is a general need for more research to understand how each of the critical success factors would be affected in different PAR implementations, and viable studies could explore any of the 31 factors from qualitative or quantitative perspectives. Indeed, we would expect there to be interrelationships between some factors, and so individual studies would be able to explore multiple critical success factors.

To achieve increased aggregation in our definition of a research agenda, we link the six CSF aggregations previously developed in Table 3 around factors affecting product, process, and supply chains. These are shown in Table 5, with some CSF aggregations notable common to all strategic choices. From this, interesting many interesting directions for investigation may result, and we suggest some potential opportunities in Figure 3.

Remanufacturing Critical Success Factor	Domain
Remanufacturing Product Design	Product Domain
Operations	Process Domain
Reverse Supply Chain	Supply Chain Domain
Knowledge and skills	Relevant to all
Flow of information	Relevant to all
Marketing	Relevant to all

Table 5: Linking remanufacturing CSFs to focal domains

Product domain research: Whilst the original design of products is unlikely to be within the control of PAR implementers, it remains important that products are remanufacturable in a PAR context, and remain remanufacturable over the various versions and iterations within the product lifecycle. Whilst there is increasingly much enthusiasm (and legislative support) for movements such as “right-to-repair” that will increasingly enable 3rd party remanufacturing, there remain many questions around the management of intellectual property, licencing, and product liability management that could be explored for PAR.

Process Domain research: Within individual PAR operations there are a multitude of CSFs that could be explored, many of which (e.g. scheduling, inspection, capacity management) present as problems common to all forms of remanufacturing. Whilst there is merit in exploring these, some of the more immediate and interesting questions are particularly to the novelty of PAR. For example, if PAR facilities are more general-purpose, what is the optimal variety of products that should be accepted? Is there merit on focusing on broad categories (e.g. electrical), on product family architectures (e.g. televisual), or specific manufacturers (Sony and Apple)? When setting up a PAR facility, how is the flexibility of technology evaluated, and how would a PAR facility make capital investment decisions for expansion? In operation, PAR facilities may require significant effort to monitor the wide variety of products passing through; how do managers inspect, monitor, and control for both effectiveness and efficiency?

Supply Chain Domain research opportunities: As with conventional remanufacturing it is expected that supply chains will play a significant role in supporting the success (or otherwise) of PAR. The increased variety of products is likely to increase the number of players within the supply chain, and so effective reverse logistics will be paramount. This

noted, it remains unclear as to how co-ordination between these would occur in PAR, particularly where multiple competing organizations become part of the same supply chain. Furthermore, how to forecast and achieve efficient flows of high-variety products in the reverse supply chain remains rather underexplored, and so this would be a sensible avenue for research.

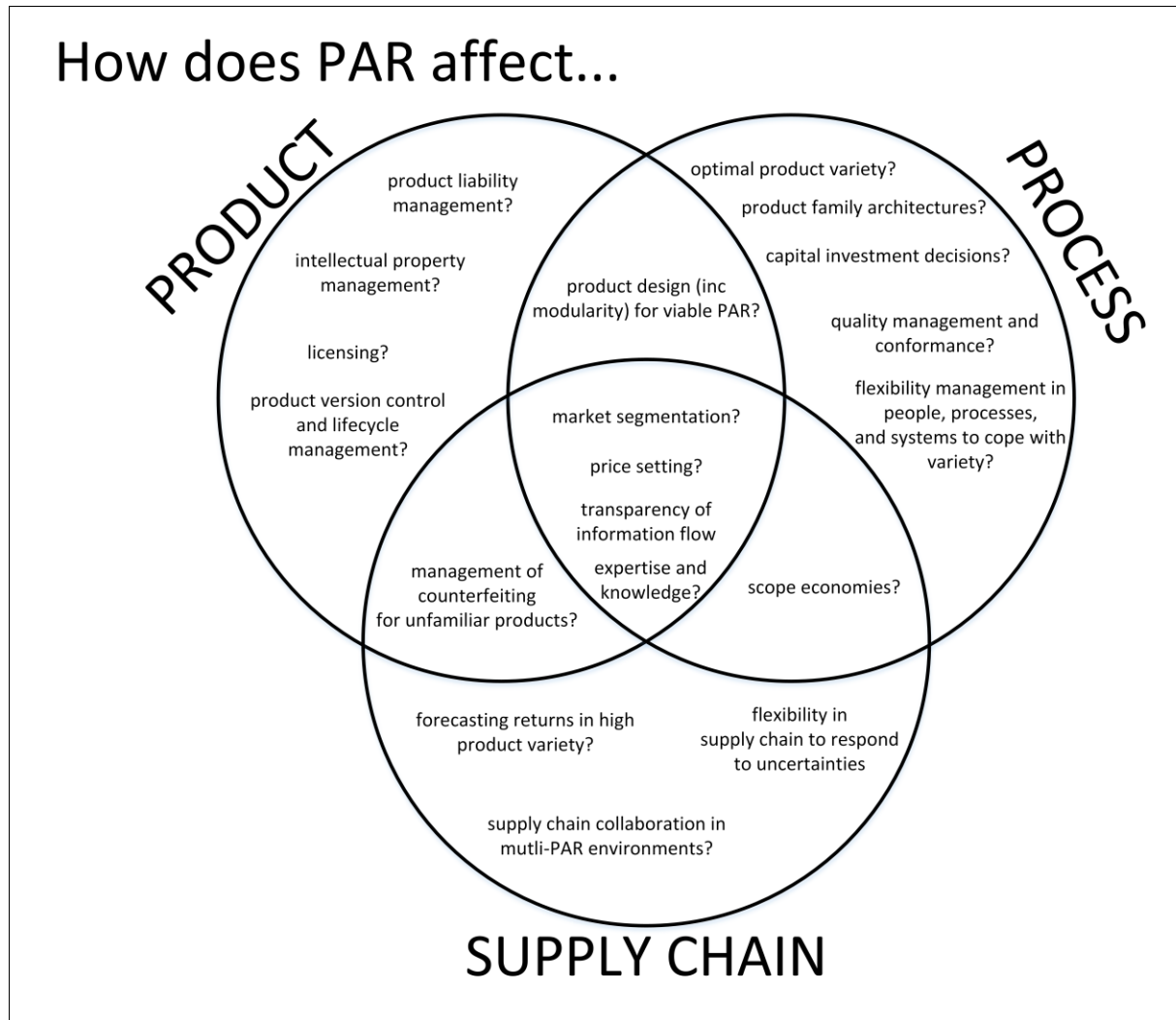


Figure 3: A three-dimensional research agenda for Product-Agnostic Remanufacturing

6. CONCLUSION

Strategy literature promotes doing things differently (innovation) as a means for firms to differentiate themselves within marketplaces, and to give competitive advantage. In this paper we develop the concept of PAR and highlight the potential strategic opportunity in adopting it within remanufacturing operations. We use theory synthesis to draw upon multiple facets of operations and supply chain management research, developing a new concept for further exploration.

However, it is essential to maintain a strong linkage between both strategy and its execution (Martin, 2010); a good idea poorly implemented serves as much purpose as a bad idea well implemented. In this conceptual work we have identified some existing approaches (e.g. Additive Manufacturing) that are already being employed in manufacturing to afford flexibility in product manufacture, as well as affecting localisation of production. By extension, we have highlighted opportunities for 3PLs as potential entrants to the market, who by virtue of their distributed warehousing and reverse logistics expertise might be well-suited to PAR operations.

Whilst we are careful not to pin the success of PAR on any given technology, observations from the Additive Manufacturing marketplace are helpful to predict trajectories. Though it has taken decades to achieve, gradually these technologies are finding their place in some mainstream manufacturing activities for spare parts and high variety production, in both centralised and decentralised applications (Rogers *et al.*, 2016, Ryan *et al.*, 2017, Hecker, 2020, Jimo *et al.*, 2021) and we find emerging accounts in recent literature of general-purpose makerspaces enabling repair functions too (Hielscher and Jaeger-Erben, 2021).

It is, of course, recognized that there are many challenges which may need to be overcome in achieving an optimal competitive commercial solution beyond the conceptual projections and anticipated contributions of technology that are proposed in this paper. For this we have developed an extensive set of Critical Success Factors for remanufacturing from the literature, from which we have developed a detailed research agenda. We believe that there is a need for further research for a much fuller understanding on the opportunities and implications throughout the supply chain, and recommend a combination of qualitative and quantitative research is employed to explore and explain the impact of PAR.

As the Circular Economy becomes increasingly important to all aspects of society and business, firms are needing to explore a range of different strategies by which to conduct themselves in more sustainable ways. For practitioners we provide a detailed discussion of the PAR opportunity, highlight the potential benefits, and articulate a detailed list of Critical Success Factors that need to be considered for remanufacturing operations. For firms interested in entering remanufacturing, we suggest that these considerations might form the basis of commercialisation explorations. For those already engaged in remanufacturing, we suggest the PAR approach might offer some competition, and they should consider how best to respond. In terms of research, the theory synthesis approach has allowed us to bridge various facets of operations and supply chain research to pose a new conceptual opportunity that has not been tackled before. We build our concept from long-established concepts such as competitiveness through manufacturing (Skinner, 1969) and the value of flexibility as a competitive weapon (Hayes and Wheelwright, 1984), but extend these to remanufacturing, and focus on technological enablers. In setting out a detailed agenda for future research, we provide a range of viable directions for future researchers.

Naturally there are limitations to our study. Whilst our conceptual work is extensively informed by literature, we have not had opportunity to explore it with empirical data. In particular, it would be useful to test the concepts with practitioners who are already actively engaged in remanufacturing, particularly to explore the economic and logistical feasibility of PAR. Furthermore, whilst our agenda is developed based on evidence from the literature review of Critical Success Factors, these are all presumed to be of equal importance; it would be useful to understand which factors are of most importance in PAR, and whether this is significantly different from conventional manufacturing.

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