INDUSTRY 4.0:
PRODUCT DIGITAL TWINS FOR REMANUFACTURING DECISION-MAKING

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Abstract

Currently there is a desire to reduce natural resource consumption and expand circular business principles whilst Industry 4.0 (I4.0) is regarded as the evolutionary and potentially disruptive movement of technology, automation, digitalisation, and data manipulation into the industrial sector. The remanufacturing industry is recognised as being vital to the circular economy (CE) as it extends the in-use life of products, but its synergy with I4.0 has had little attention thus far. This thesis documents the first investigating into I4.0 in remanufacturing for a CE contributing a design and demonstration of a model that optimises remanufacturing planning using data from different instances in a product's life cycle.

The initial aim of this work was to identify the I4.0 technology that would enhance the stability in remanufacturing with a view to reducing resource consumption. As the project progressed it narrowed to focus on the development of a product digital twin (DT) model to support data-driven decision making for operations planning. The model's architecture was derived using a bottom-up approach where requirements were extracted from the identified complications in production planning and control that differentiate remanufacturing from manufacturing. Simultaneously, the benefits of enabling visibility of an asset's through-life health were obtained using a DT as the modus operandi. A product simulator and DT prototype was designed to use Internet of Things (IoT) components, a neural network for remaining life estimations and a search algorithm for operational planning optimisation. The DT was iteratively developed using case studies to validate and examine the real opportunities that exist in deploying a business model that harnesses, and commodifies, early life product data for end-of-life processing optimisation. Findings suggest that using intelligent programming networks and algorithms, a DT can enhance decision-making if it has visibility of the product and access

to reliable remanufacturing process information, whilst existing IoT components provide rudimentary “smart” capabilities, but their integration is complex, and the durability of the systems over extended product life cycles needs to be further explored.

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Next, the School of Mechanical Engineering for covering tuition fees and for the Engineering and Physical Sciences Research Council (EPSRC) and the MTC for the PhD Scholarship. Without their funding I would not have been able to pursue this research and subsequent career path.

Finally, I am very greatful to Natalia Hartono for adapting the Bee's Algorithm script for application in this research and I wish to thank my family and friends for their continued support.

Preface

After 10 years as a manufacturing engineer, I felt the need to change course. During those years I had become a competent project manager, but I was never satisfied in my role as ultimately, I was supporting mass production, as a cog in the wheel of a large corporation. I had become disheartened with the "make it quicker, cheaper, faster" demands of the daily work life and needed to look for an opportunity to use some of what I had learned to contribute to the protection of our planet.

I had pondered pursuing and academic career many times but as I handed my notice in the same week that I paid of my student loan I knew the PhD titled "Robotic Disassembly as an Enabler to Remanufacturing" was what I wanted to target. I was very fortunate to have been accepted into the University of Birmingham to study this subject.

The first two years were challenging but it became much harder from January 2020 when the Covid-19 pandemic hit Europe. Access to the lab stopped and I had to look at how I was going to finish my research not knowing when, if at all, we would be able to return. I had to look for an alternative thesis ending that could be progressed from home, one that would lead me down the digital twin path for over a year. At the same time, part-time work at the university ceased and I was forced to take on an almost full-time warehouse job at the peak of the pandemic. Later that year I would experience a health scare that would lead to heart surgery and seven months of discomfort and regular hospital trips. Despite all of the above I am happy with the choices that I have made, the work that I have completed, the challenges that I have overcome, and I remain greatful to those who have made it all possible.

List of Publications

1. Kerin, M. and Pham, D.T. (2020), "Smart remanufacturing: a review and research framework", *Journal of Manufacturing Technology Management*, Vol. 31, No. 6. https://doi.org/10.1108/JMTM-06-2019-0205

2. Kerin, M. and Pham, D.T. (2019). "A review of emerging industry 4.0 technologies in remanufacturing", *Journal of Cleaner Production,* Vol. 237. https://doi.org/10.1016/j.jclepro.2019.117805

3. *Under review with The International Journal of Advanced Manufacturing Technology* - Kerin, M., Pham, D.T., Huang, J. and Hadall, J. (2021). “A generic asset model for implementing product digital twins in smart remanufacturing”. https://doi.org/10.21203/rs.3.rs-186288/v1

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List of Symbols

α	An action in the remanufacturing function that causes an environmental impact (shipping, disassembly, storage etc.)
λ	Time functions
ca	Cost of assembling product per unit of time
cc	Cost of recycling component
cd	Cost of disassembly per unit of time
cdp	Cost of disposal
ch	Cost of holding component per unit of time
cp	Cost of procuring component
cph	Cost of preserving component for storage
cr	Cost of reincarnating component per unit of time
cru	Component revenue from reuse
cs	Cost of shipping per km
cu	Cost of preparing component for reusing per unit of time
ed	Environmental impact of disassembly of component per unit of time
edp	Environmental impact of disposal
eh	Environmental impact of holding per unit of time
ep	Environmental impact associated with the procurement of a part
er	Environmental impact per unit of time in reincarnation
erc	Environmental benefits associated with reusing the material over virgin material
eru	Environmental benefits associated with reusing the component over a new component

es	Environmental impacts of shipping
eu	Environmental impact as a result of preparing a component for reuse
f	Remanufacturing facility
fr	Routes through to reincarnation from reuse
fu	Routes through to available for sale from reuse
i	Product
j, k...z	Components
l	Distance in km
m	Missing component
mrc	Material revenue from recycling
nc	Need to recycle
nd	Need to disassemble component 1 or 0
ndp	Need for disposal
nh	Need to hold component
nr	Need to reincarnate component
nsl	Component destined for recycling or disposal
qi, qj	Product quality, component quality
qmin	Min quality of component for use in remanufactured product
ro	Routes through the remanufacturing function
sl	Component destined for reincarnation or reuse
ta	Time to assemble product
td	Time it takes to disassemble
th	Time component in storage
tr	Time to reincarnate component

tu	Time to prepare component for reuse
x	Represents reincarnation, reuse, recycling, or disposal (1, 2, 3 or 4)
y	Impact categories (energy, material consumption, emissions to air and water and waste generation)
B	Management of unwanted assent burden
CCA	Cost of component assembly
CCC	Cost of component recycling
CCD	Cost of component disposal
CCR	Cost of component reincarnation
CCS	Cost of component storage
CCU	Cost of component reuse
CN	Connections
COS	Cloud Object Storage
CPD	Cost of product disassembly
CPF	Cost of product finishing
CPR	Cost of product recovery
CRF	Cost of remanufacturing function
DD	Digital Twin Data
DT	Digital Twin
E	Environmental benefits
ECA	Environmental impacts of component assembly
ECC	Environmental impacts of component recycling
ECD	Environmental impacts of component disposal
ECP	Environmental impacts of component procurement

ECR	Environmental impacts of component reincarnation activities
ECS	Environmental impacts of component storage
ECU	Environmental impacts of reuse
EPD	Environmental impacts of product disassembly
EPR	Environmental impacts of product recovery
ERF	Environmental impact from remanufacturing function
ES	Environmental savings
H	Number of man-hours
J	Function representing the link between process time and man-hours
Nu	Need to reuse
OS	Optimal solution
P	Profit
PE	Physical Entity
R	Volume-based ratio of reused, remanufactured, and recycled material to disposal
SP	Sales price of the remanufactured product
Ss	Services for PE and VE
TQ1	Function representing impact of q on disassembly time
TQ2	Function representing impact of q on reincarnation time
TQ3	Function representing impact of q on reuse time
TS	Function representing impact of second-life destination on disassembly time
VE	Virtual Entity
WD	Weighted deviation

Nomenclature

AAS	Asset Administrative Shell
AI	Artificial Intelligence
AM	Additive Manufacturing
API	Application Programming Interface
AR	Augmented Reality
BA	Bees Algorithm
BDA	Big Data Analytics
BoL	Beginning of Life
BoP	Bill of Process
CE	Circular Economy
CM	Cloud Manufacturing
COS	Cloud Object Storage
CPQ	Certainty of Product Quality
CPS	Cyber Physical Systems
CSF	Critical Success Factor
CT	Cycle-time
D4S	Design for Sustainability
DCD	Data Carrying Devices
DfAM	Design for Additive Manufacturing
DfD	Design for Disassembly
DfR	Design for Remanufacture
DfS	Design for Service
DMM	Decision-Making Module
DSP	Disassembly Sequence Planning
DT	Digital Twins

DTA	Digital Twin Aggerate
DTE	Digital Twin Environment
DTI	Digital Twin Instance
DTP	Digital Twin Prototype
eBoM	Engineering Bill of Materials
ECU	Engine Control Unit
EoL	End of Life
EI	Emerald Insight
EIS	Enterprise Information System
ERP	Enterprise Resource Planner
ELV	End-of Life Vehicle
GPS	Global Positioning System
GUI	Graphical User Interface
HDOR	Heavy Duty Off-Road
HiVE	High-value entity
HMI	Human-Machine Interface
ICT	Information and Communication Technology
I4.0	Industry 4.0
IoT	Internet of Things
IP	Intellectual Property
IR	Industrial Robot
LCA	Life Cycle Analysis
mBoM	Manufacturing Bill of Materials
MES	Manufacturing Execution System
MoL	Middle of Life
MRO	Maintenance Repair Overhaul
MSDS	Material Safety Data Sheets

NA	Nature-inspired Algorithms
OEM	Original Equipment Manufacturer
PCB	Printed Circuit Board
PLC	Programmable Logic Controller
PLM	Product Lifecycle Management
PQ	ProQuest
PPU	Pay Per Use
PSS	Product Service System
PSST	Passive Self-Sensing Tags
QMS	Quality Management System
QR	Quick Response
RAMI 4.0	Reference Architectural Model Industrie 4.0
RasPi	Raspberry Pi
rBoM	Remanufacturing Bill of Materials
rBoP	Remanufacturing Bill of Process
RFID	Radio Frequency Identification
RMS	Reconfigurable Manufacturing System
SBoM	Service Bill of Materials
SD	ScienceDirect
SME	Small-Medium Enterprises
SRDM	Smart Recovery Decision-Making
TCP	Transmission Control Protocol
UML	Unified Modelling Language
UDP	User Datagram Protocol
UTC	Coordinated Universal Time
VR	Virtual Reality
WEEE	Waste Electrical and Electronic Equipment

WIP	Work in Progress

1 INTRODUCTION

1.1 Background

Remanufacturing is defined as the steps required to change a product into as new with at least equivalent performance and warranty of new (British Standards Institution, 2010). As remanufacturing is a key strategy to increase resource circularity and sustainability (Potting, 2016), the remanufacturing sector is growing, so too is the research interest to support it.

Research into smart remanufacturing systems is increasing in popularity with recent discussions focusing on how technology from Industry 4.0 (I4.0) as applied in manufacturing can increase efficiency and digitalisation in remanufacturing (Wenjie *et al.*, 2016, Yeo, Pepin and Yang, 2017, Yang *et al.*, 2018). However, differences between manufacturing and remanufacturing mean that direct application of I4.0 technology from the former into the latter may not be practicable. The remanufacturing process's inbound supply is highly variable in both quantity and quality. Remanufacturers may have to process dirty, distorted, worn components, deal with one-way or irreversible fittings, and conduct partial, targeted and destructive disassembly operations (Touzanne, Henrioud and Perrard, 2001) depending on the business and customer needs. The route and steps that follow disassembly often vary and can lead to hybrid assemblies combining new and refurbished components. Remanufacturing product and component demand is also highly volatile (Guide *et al.*, 2000). All of these things combined make for complex business models and processes that demand flexibility that up until recently could only be realised with manual labour. This has led to a sector that exhibits low levels of technology utilisation. Limited certainty and longevity make large capital investments, associated with "smart" remanufacturing, risky. However, as technology and information systems advance and

become more accessible, this opens up new opportunities that could enable better management of uncertainties and process variability, two of remanufacturing's main challenges.

The motivation of this research was to reduce waste to landfill by focusing on, and empowering the remanufacturing sector, whilst documenting findings related to potential opportunities with others. The aim of this research was to promote the exploitation of Industry 4.0 technologies in the remanufacturing sector. This makes it pertinent to the stakeholders in the umbrella project AUTOREMAN funded by EP/N018524/1, that looks to investigate autonomous remanufacturing opportunities in this sector, and interesting to legislators, researchers and those involved in environmental initiatives such as Net Zero.

1.2 Boundaries of this Research

With respect to minimising energy leakage as a CE strategy, remanufacturing sits between reuse and recycling (Geissdoerfer *et al.*, 2017). This work focuses specifically on the remanufacturing sector, but it needs to be recognised that components from products that are recovered for remanufacturing can end up going directly into reuse applications or if un-desirable, recycling or disposal. Similarly, the same components could be repaired or refurbished for use as replacement parts to feed maintenance, repair, overhaul (MRO), and service activities, so the different strategies are interconnected. The way in which performance and product life can be tracked through condition monitoring systems, for all of these activities further highlights their close association and overlap. However, preventative maintenance, MRO and servicing activities work to extend the longevity of the product in its current life, whereas remanufacturing works to provide end-of-life (EoL) products a second life with at least equivalent performance and warranty of its first. The boundaries to this work are then as follows. Only products that have the potential to be processed by remanufacturers for the

purpose of second life (or multiple lives) are considered along with the process of remanufacturing that product. Monitoring the product in-life for EoL planning is in scope but how components may be used in maintenance or other non-remanufacturing CE strategies is not.

1.3 Aim and Objectives

The initial guiding research question was "how can we use emerging digital technologies to improve stability (as defined by (Cambridge Dictionaries Online, 2021) as "a situation in which something such as an economy, company, or system can continue in a regular and successful way without unexpected changes") in remanufacturing operations with a view to reducing resource consumption and aid circular economy strategies?"

The objectives were as follows:

1. To investigate the state-of-the-art in the use of emerging digital technologies in remanufacturing for a circular economy.
2. To clarify the depth of application of I4.0 technologies currently in remanufacturing at different levels of the industry to develop a research agenda and framework as outputs.
3. To extract the gaps and opportunities in remanufacturing that can be supported by the advanced technology.
4. To select a gap / opportunity and develop an emerging technology to fill it validating through demonstration the technology in its application.

1.4 Methodology

The overall research methodology was to explore emerging technologies and how they could be used in remanufacturing. Initially, defining remanufacturing as the sector in focus framed this work as applied research. Yet, at the outset, no problem was identified and very few studies

had been discovered in this field that could offer a hypothesis to test. It was therefore necessary to start with an exploratory method working to the assumption that opportunities exist to use emerging technology in remanufacturing to improve sustainability, but they had not yet been captured. A systematic literature review formalised the approach to derive the opportunities. Once the trends and gaps were understood the methodology changed, becoming 1) more conceptual to develop a solution to fit the opportunities and 2) operations-based to replace intuitive business decision-making processes with data-driven ones.

1.5 Thesis Structure

This thesis uses the 'Alternative Format' as Chapters 2 and 3 contain publications and Chapter 4 is a submitted manuscript. The content of each chapter is described below.

Chapter 1 – **Introduction** - presents a general introduction to the topics in question, an aim and objectives, the research approach, and an overview of the thesis content.

Chapter 2 - Smart Remanufacturing - contains a published systematic literature review on smart remanufacturing considering its place in a circular, I4.0 future. It is the first to study "smart remanufacturing" whilst supporting CE principles. Its uniqueness lies in its focus on the remanufacturing industry and the sustainable application of I4.0 enablers. Form the review, a research framework and agenda are developed and documented. Findings suggest that smart remanufacturing assumes the utilisation of I4.0 technologies on the product to be remanufactured as well as the remanufacturing processing equipment and business management systems. Nine technology-based research agenda items are identified and related to the product, process, or management systems. With this knowledge, a deeper review into the emerging technologies specifically in the remanufacturing sector is necessary as with such a new and broad subject matter, a greater understanding of state-of-the-art was required.

Chapter 2.9 - Emerging I4.0 Technology in Remanufacturing - reviews and documents the research trends and gaps in the use of I4.0 in the same sector as Chapter 2. Results suggest there is a need to explore the connection of cyber-physical systems to the IoT to support smart remanufacturing, whilst aligning with evolving information and communication infrastructures and circular economy business models. Five of the identified gaps spearhead the remaining chapters. These include, 1) little consideration has been given to the exploitation of data carrying opportunities of already "smart" products for remanufacturing, 2) currently there are few demonstrations of existing smart I4.0 technologies being applied in remanufacturing, 3) there are no published demonstrations that show how virtual product / process twins or big data could be used in remanufacturing 4) opportunities exist in the exploration of potential links between remaining product life and core supply management or remanufacturing process strategy design and 5) there is an opportunity to further develop sustainable business models that utilise I4.0 specifically for the remanufacturing industry.

Chapter 4 - Digital Twins for Remanufacturing - combines gaps 1 and 3 to look at digital twins for high value assets that already have some level of "smart" functionality. Having extracted the system requirements from the industry needs, a class model is developed to support the implementation of product digital twins for smart remanufacturing.

Chapter 5 - I4.0 Technology in Digital Twins for Remanufacturing - document the development of a demonstration system that incorporates a high-value asset simulator and digital twin prototype to explore decision-making in remanufacturing whist demonstrating I4.0 technology combining gaps 2-5. A greater understanding of how product DT requirements can be realised at an operational level is achieved along with proof and a methodology that existing platforms and off-the-shelf components can be used for laboratory based IoT experiments.

Chapter 6 - Product Digital Twin Driven Decision-Making in Remanufacturing - draws the themes of the previous chapters to model a decision-making module (DMM) that forms part of the DTs sustainable forward planning capability for product remanufacturing. A case study is used to assess the impact of using the DT and DMM in this way.

Chapter 7 - Conclusion – wraps up the thesis with a summary of contributions and further work.

The introduction and conclusion bookend five main chapters. The relationships between the chapters are shown in Figure 1-1. The high-level objectives, methods and outputs are documented to help navigate the content. The main sections in chapters 2 and 2.9 have already been published and chapter 4 is in peer-review at time of writing. These chapters are therefore presented in a paper style format, each with their own abstract, introduction and references for completeness. The final section in each of these chapters is written to help the reader understand the links between, and to clarify pertinent points that may be missing from, the published sections. Citations included in these sections are included in the final reference list. The style used from chapters 5 onwards is more traditional with the references presented after the conclusion.

1.6 Summary

This chapter puts the research into context. It starts with a short section detailing the background and boundaries to the work followed by the aim, associated objectives, and the method, before concluding with an overview of how the thesis is structured.

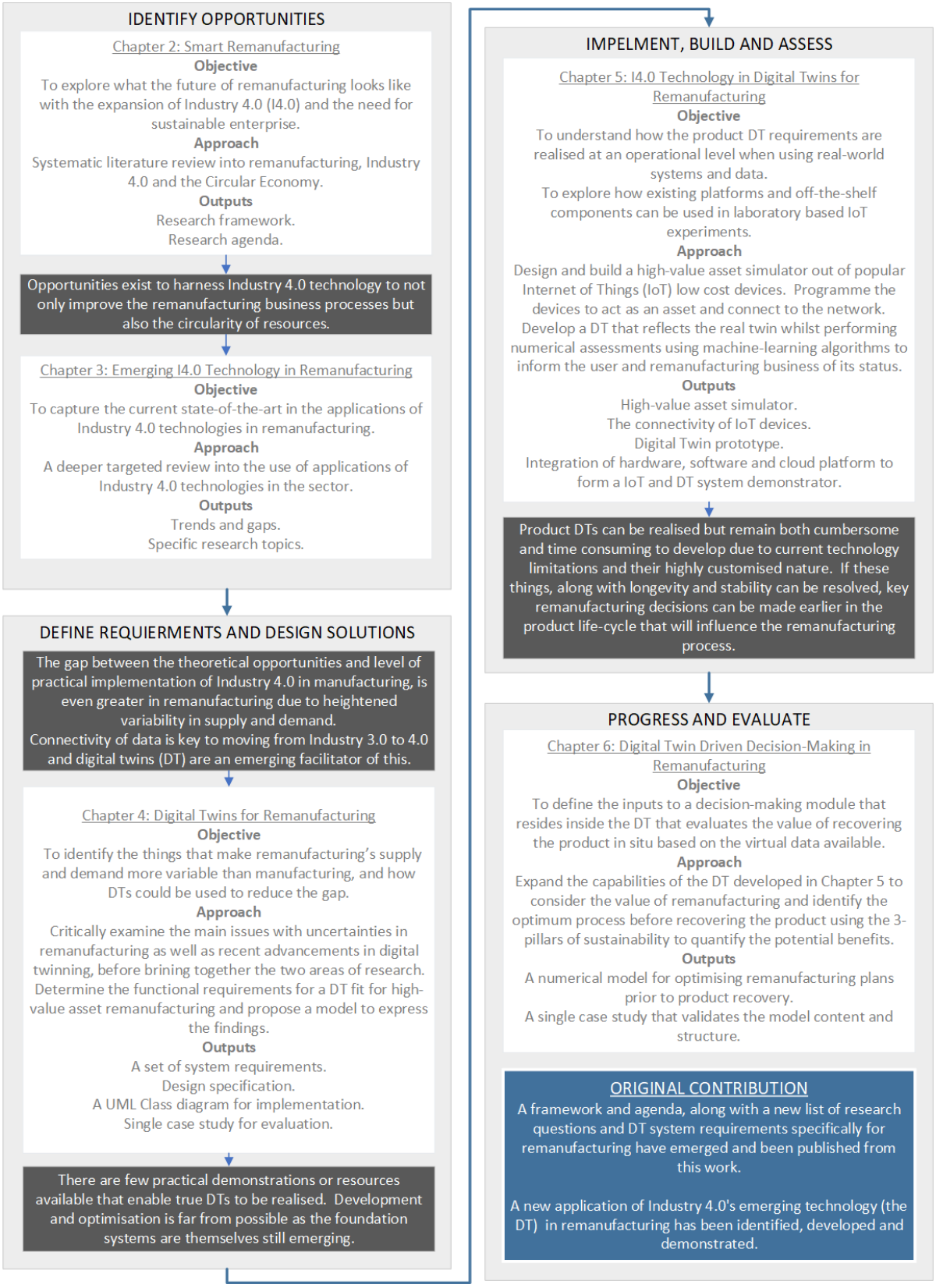


Figure 1-1 - Main chapters in this thesis and how they relate to one another

2 SMART REMANUFACTURING

SMART REMANUFACTURING: A REVIEW AND RESEARCH FRAMEWORK

Published review.

Mairi Kerin†, Duc Truong Pham†

(2020) "Smart remanufacturing: a review and research framework", *Journal of Manufacturing Technology Management*, Vol. 31, No. 6. https://doi.org/10.1108/JMTM-06-2019-0205

M.K. Conceived and designed the review, performed the analysis, interpreted the data, and wrote the manuscript. D.T.P. supervised the work, supported the execution and interpretation of the findings, critiqued, and edited the manuscript and advised on the journal to which the article would be submitted.

† School of Mechanical Engineering, University of Birmingham

2.1 Abstract

Purpose - To review the state-of-the-art in smart remanufacturing, highlighting key elements of an Industry 4.0 future that supports circular economy principles, and offer a conceptual framework and research agenda to accelerate digitalisation in this sector.

Approach - The Scopus, Web of Science and Science Direct databases and search terms "Industry 4.0", "Internet of Things", "Smart manufacturing" and "Remanufacturing" were used to identify and select publications that had evidence of a relationship between those keywords. The 329 selected papers were reviewed with respect to the triple bottom line (economic, social and environmental). The study benefited from advanced text quantitative processing using NVivo software and a complete manual qualitative assessment.

Findings - Changes in product ownership models will affect the remanufacturing industry, with the growth of product-service-systems seen as an opportunity to re-circulate resources and create value. This is being supported by changes in society, user expectations and workforce attributes. Key to the success of remanufacturing in an Industry 4.0 future is the uptake of existing and emerging digital technologies to shorten and strengthen links between product manufacturers, users and remanufacturers.

Originality - Remanufacturing is recognised as a key circular economy strategy, which in turn is an important research area for development in our society. This article is the first to study "smart remanufacturing" for the circular economy. Its uniqueness lies in its focus on the remanufacturing industry and the sustainable application of Industry 4.0 enablers. The findings are used to create a framework that links to the research agenda needed to realise smart remanufacturing.

2.2 Introduction

The cost of waste to the environment, the depletion of natural resources, increasing commodity costs, improvements in technology and changes in consumer demands are building momentum in the support of a circular economy (CE) of which remanufacturing is a key strategy (Preston, 2012). As one of the nine CE strategies (Potting, 2016), remanufacturing is defined as the "steps required to change the product into as-new with at least equivalent performance and warranty of new" (British Standards Institution, 2010). It has the potential to be worth €90bn to the EU economy by 2030 (Oakdene Hollins, 2018) making it a particularly interesting subject for industry-based readers.

Industry 4.0 (I4.0) builds on the three previous revolutions with the intelligent networking of machines and processes (Federal Ministry for Economic Affairs and Energy, 2019). The Internet of Things (IoT) is an infrastructure that connects existing and emerging, real and virtual technologies enabling advanced services (International Telecommunication Union, 2012). I4.0 and IoT are closely interconnected (Schweichhart, 2016), and their hyper automation and connectivity enables the realisation of smart factories (Stock and Seliger, 2016) built on Cyber Physical Systems (CPS) (Khaitan and McCalley, 2015) operated by artificial intelligence (AI), IoT, big data and robotics (Park, 2017). In manufacturing, the application of smart factory principles and technologies is already underway (Ghobakhloo, 2019) driven by a number of Original Equipment Manufacturers (OEM) (Tolio *et al.*, 2017), and research consortia (Bueno, Girot and Gutiérrez-Orrantia, 2017). Remanufacturers can learn from these applications but as they generally operate in a lower technology environment (Butzer and Schötz, 2016) with different management strategies, a smart factory vision specifically for this industry in needed.

Whist there has been an increase in the attention given to remanufacturing (Yang, Ong and Nee, 2014), and frameworks on the application of I4.0 technologies and their potential to support the

CE are emerging (Kamble, Gunasekaran and Gawankar, 2018), the remanufacturing industry is rarely the main focus of research. The present study will look to fill this gap by providing a framework for remanufacturing to support the transition from a traditionally highly manual and unstable industry, to an automated, data-driven, smart one using I4.0. In order to build the framework, a firm understanding of key I4.0 technologies and their potential impact on the industry is required.

The next section presents the review methodology and an overview of findings (section 2.3). Identified trends in the use of I4.0 technologies for remanufacturing are outlined in section 2.4. Section 4 explores the impact of I4.0 technologies in remanufacturing for the CE categorised according to economic, social and environmental factors. Section 5 proposes a framework and research agenda to support the digitalisation of remanufacturing for the CE. Section 2.6.2 concludes the paper.

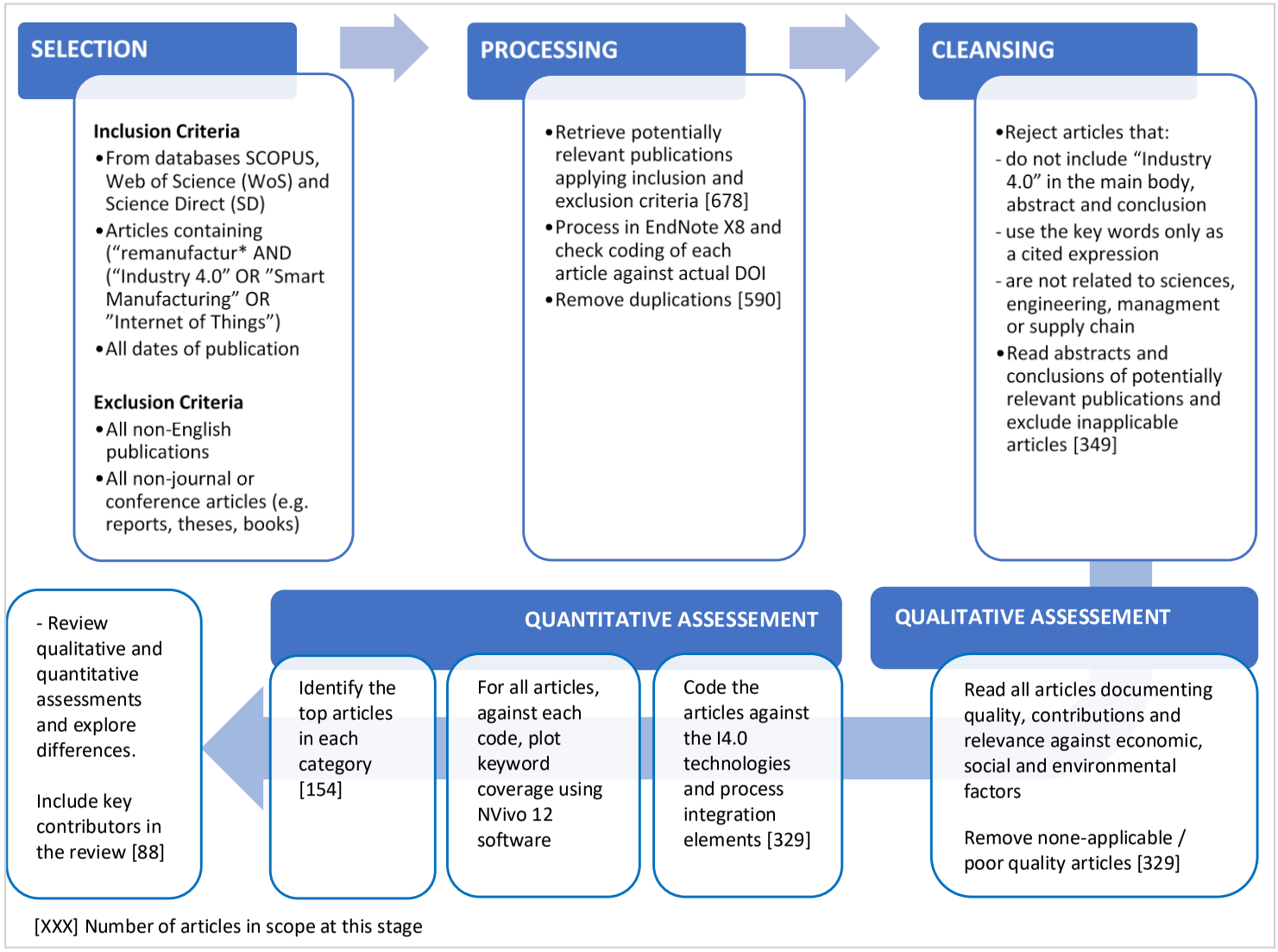
2.3 Literature Review

A methodical approach to this inductive review (Miles, Huberman and Saldaña, 2020) was adopted to help develop a reliable knowledge base (Tranfield, Denyer and Smart, 2003), generate early research questions and survey the state-of-the-art, before proposing future hypotheses and a research agenda as outputs.

2.3.1 Research Methodology

A systematic process (Durach, Kembro and Wieland, 2017) was used, starting with an open-dated search of three academic databases. To avoid missing key literature due to different labelling of the same concepts, search terms included “Industry 4.0”, “Internet of Things” OR “Smart Manufacturing” AND “Remanufactur”. Figure 2-1 summarises the inclusion and exclusion criteria, processing, cleansing and assessment.

Figure 2-1 Literature review process adapted from Durach et al. (2017)



The inclusion of at least one keyword in the body of the text was critical to its retention. Articles that did not contain "remanufacturing" in the body of the text were not automatically excluded as there is currently a lower level of smart enablers used in remanufacturing compared to other smart-circular strategies (Alcayaga, Wiener and Hansen, 2019) and lessons can be learned for application in this emerging area. However, articles that did not contain "Industry 4.0", "Smart Manufacturing" or "Internet of Things" were rejected.

This resulted in the identification of 349 pertinent articles from 2011 to 2020. (Although the search was completed in August 2019, it uncovered in-press articles due to appear in 2020.) Figure 2-2 shows the distribution of these articles and the year-on-year growth in the combined utilisation of the keywords, justifying the timeliness of this research. (The 2019/20 bars are hashed due to the mid-year search.) Figure 2-3 shows that the leading journal outlets in this field are Procedia CIRP, Journal of Cleaner Production and Procedia Manufacturing.

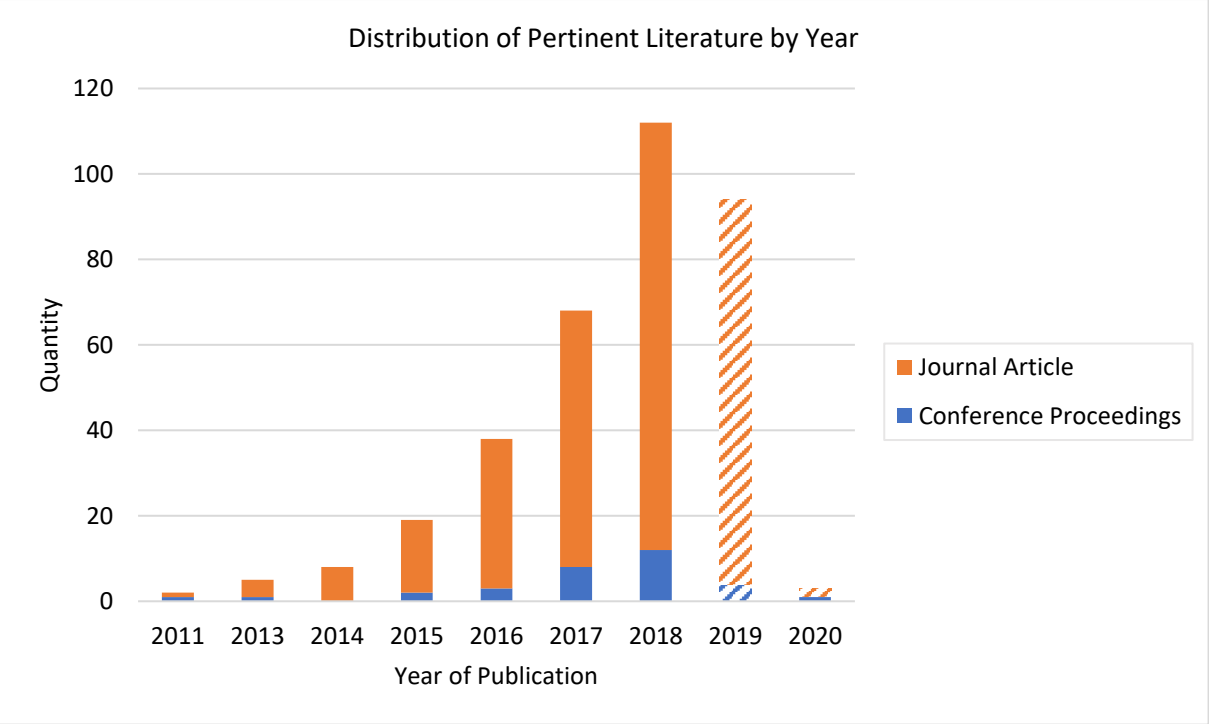


Figure 2-2 Distribution of articles identified in the keyword search Aug '19, post cleansing

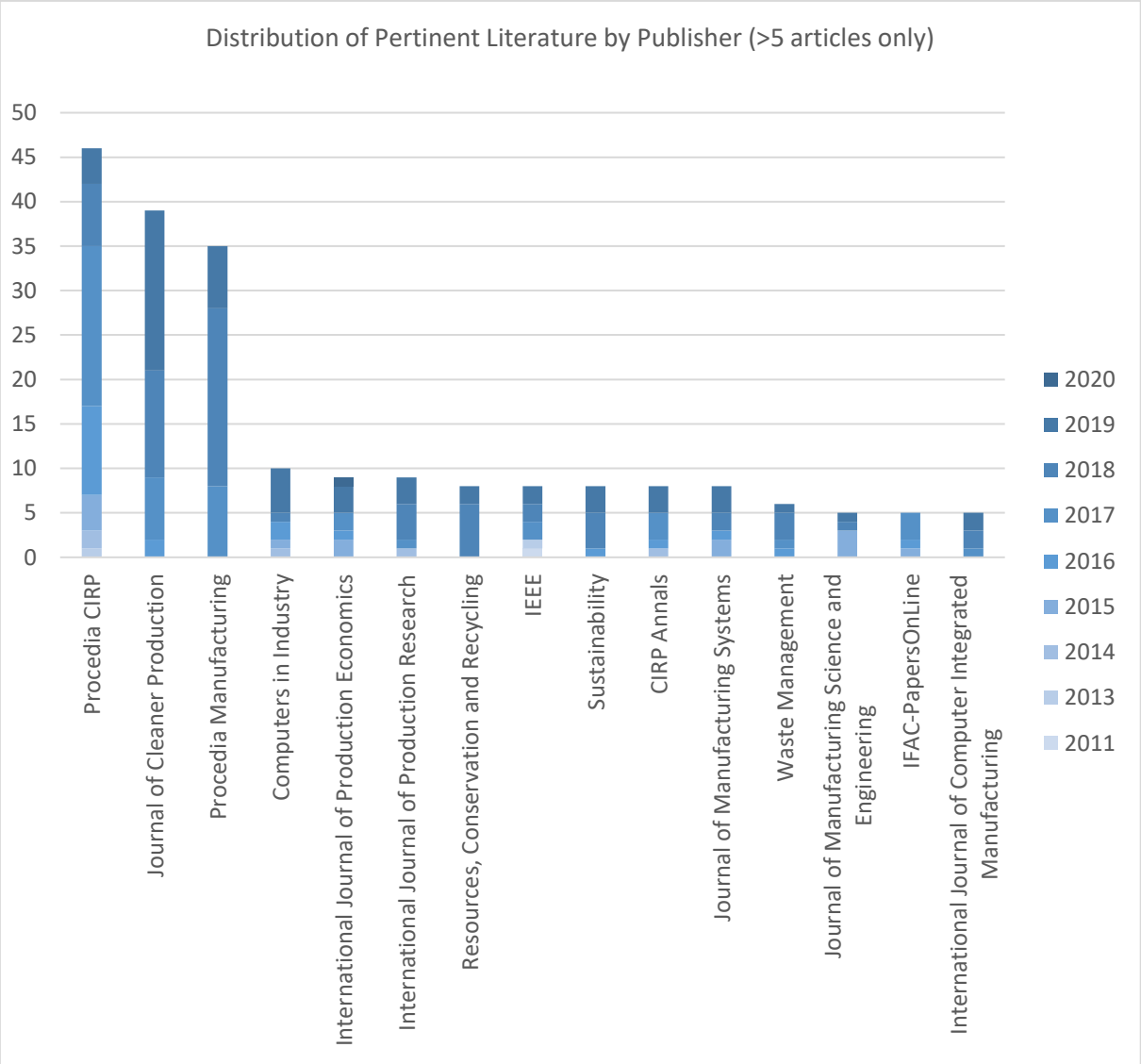


Figure 2-3 Distribution of relevant literature by journal outlet

329 of the 349 articles were cleansed for coding in NVivo12 to provide a quantitative assessment of contribution based on the coverage of the database search keywords in addition to I4.0 technologies and process integration elements adapted from Kamble, Gunasekaran and Gawankar (2018)'s sustainability framework. 20 articles were either of poor quality, unavailable or not readable to NVivo12. This assessment offered an insight into the key themes and contributors in this field. Remaining articles were ranked against the different search codes based on their individual coverage as 1st-5th= highly relevant, 6th-10th= relevant, 11th-20th= mentioned. The coverage of keywords was measured. Additionally, a qualitative assessment

of the same articles was conducted by the two authors involved. Differences of opinion were rare and resolved through discussion.

2.3.2 Descriptive Findings

From the quantitative assessment of each code 154 articles appeared at least once in the top 20 signifying the sporadic distribution of the findings. The top 20 articles identified as containing the greatest coverage of all coded search terms are presented in Figure 2-4 with their weighted relevance to each coding term (as described in columns "Keywords for Coding") documented in Table 2-1.

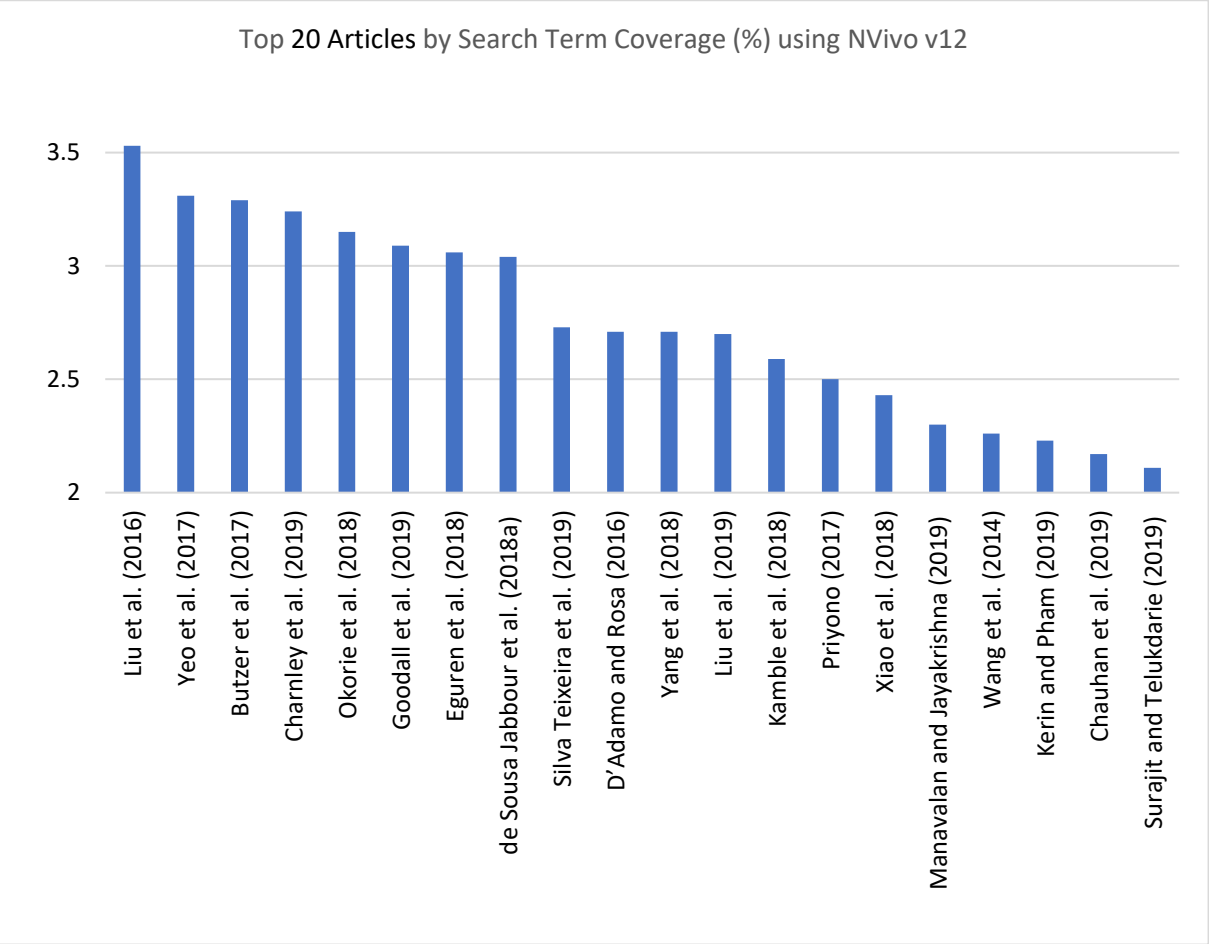


Figure 2-4 Key articles based on assessment using coding methods and NVivo software

Table 2-1 Coding table showing the top 20 articles by total coverage only

KEY Highly relevant 3 Relevant 2 Mentioned 1		Keywords for Coding													
Database search terms			*	*	*	*									
Ranking	Article	Circular economy, CE	Remanufactur(e/ed/ing)	Industry 4.0, I4.0	Smart (re)manufacturing	Internet of things, IoT	Robot	Additive manufacturing, AM, 3D printing	Big data analytics, BDA	Cloud Computing, CC, Cloud manufacturing, CM	Simulation, prototyping	Augmented reality, AR	Advanced materials, self-healing	Human-(machine/robot) collaboration, HMC, HRC	System(s) integration, process integration
1	Wenjie *et al.* (2016)		3	3											
2	Yeo, Pepin and Yang (2017)		3				1					1			
3	Butzer *et al.* (2017)		3	1								3			
4	Charnley *et al.* (2019)		2								2				
5	Okorie *et al.* (2018)		3												
6	Goodall, Sharpe and West (2019)		1								3				
7	Eguren *et al.* (2018)		3												
8	de Sousa Jabbour *et al.* (2018a)			3	1	3		1		1					
9	Silva Teixeira *et al.* (2019)		1								3				
10	Yang *et al.* (2018)		2		2										
11	Kamble, Gunasekaran and Gawankar (2018)			3	2				1		1	2			3
12	Xiao *et al.* (2018)		2												
13	Manavalan and Jayakrishna (2019)	3		1		1									
14	Wang *et al.* (2014)		1							2					
15	Kerin and Pham (2019)		1				1					2			
16	Chauhan, Sharma and Singh (2019)	1		3											
17	Surajit and Telukdarie (2019)			1								1		1	
18	Ding *et al.* (2018)		2						2						
19	Pagoropoulos, Pigosso and McAloone (2017)	3				1			1						
20	Rajput and Singh (2019)			3		1									2

NOTE: Due to limited findings the codes "Advanced materials, self-healing" and "Human-(machine/robot) collaboration, HMC, HRC" were ranked differently as follows: 1st-2nd= highly relevant, 3rd-4th= relevant, 5th-8th = mentioned.

Interestingly, the article identified as having the greatest search term coverage was Wenjie *et al.* (2016) who compared I4.0 for remanufacturing with blood circulation systems. During the qualitative assessment the same article was deemed to be not so relevant to this review. This contradictory result suggests caution should be employed when performing quantitative data assessments alone in this emerging area and backs the authors decision to read all articles in parallel to provide qualitative input. In general, the two research methods align. Findings suggest there is an increase in research being conducted in remanufacturing, I4.0 and the CE individually but there is no review that considers all three in detail.

In remanufacturing, Butzer *et al.* (2016) identify sector challenges and how these could be resolved with I4.0 technology but at a very high level, lacking thoroughness. Trends and gaps are documented (Kerin and Pham, 2019) and detailed exploration of remanufacturing I4.0 is offered in specific applications (Wang *et al.*, 2014, Yang *et al.*, 2018), regions (Eguren *et al.*, 2018) or both (Yeo, Pepin and Yang, 2017, Xiao *et al.*, 2018). A popular emerging sub-topic is remanufacturing process modelling with inputs from I4.0 technologies (Ding *et al.*, 2018, Goodall, Sharpe and West, 2019). Outlying articles exist on advanced or self-healing materials, but as can be seen from the lack of rankings in this column, it is not a core research area.

Away from remanufacturing, articles that synergise I4.0 and CE are focused on supply chain (Pagoropoulos, Pigosso and McAloone, 2017, Manavalan and Jayakrishna, 2019), its management (Chauhan, Sharma and Singh, 2019, Rajput and Singh, 2019, Surajit and Telukdarie, 2019) or manufacturing. In manufacturing they generally report on the benefits before presenting research agendas, models, architectures, roadmaps and/or frameworks for businesses or researchers to follow (Carvalho *et al.*, 2018, de Sousa Jabbour *et al.*, 2018a, de Sousa Jabbour, 2019, Nascimento *et al.*, 2019). The output of Man and Strandhagen (2017) is similar, but interestingly they are more cautious in their appraisal of I4.0. The framework by

Kamble, Gunasekaran and Gawankar (2018) was adapted to form the search term codes so there is little surprise that it makes the top 20 but it does little more than tabulate I4.0 technologies (that are better presented in other works) and the I4.0 principles from Carvalho *et al.* (2018).

Ghobakhloo (2018) offers subtly different I4.0 technologies and principles in their architecture and roadmap for transitioning but again this is for the manufacturing sector. Additionally with reference to Charnley *et al.* (2019) and Okorie *et al.* (2018), (4th and 5th respectively) both articles are deemed relevant, but it is another article that they co-authored (Okorie *et al.*, 2018) that the qualitative assessment identifies as the most interesting to this work. They extensively survey the state-of-art in CE-I4.0 methodologies on the 9R's (refusing, rethinking, reducing, reusing, repairing, remanufacturing, refurbishing, repurposing, recycling, and recovering) recommending a reduced scope, down from the 9R's for more detailed research, which underlines the need for this review. Whilst the above-mentioned articles are relevant (each in agreement that I4.0 businesses will increasingly rely on intelligent data to deliver new services), they do not exclusively explore "smart" remanufacturing in the CE. It is therefore assumed that they are only partly applicable.

The objective of this paper is to develop a research agenda to support the realisation of smart remanufacturing. The assumption that existing I4.0 manufacturing research is only partly applicable to remanufacturing generates new research questions – What aspects of the existing I4.0 technology and principles already researched are applicable but specific to remanufacturing? What is required to make remanufacturing smart and sustainable?

This article shall attempt to answer these questions following a summary of I4.0 technologies for remanufacturing (section 2.4) and the results of the literature review that is categorised using

the triple bottom line (section 2.5). Key findings are noted throughout the article and registered using a hashtag and number, e.g. [#1]. These are then used to formulate the framework.

2.4 I4.0 Technologies for Remanufacturing

Smart remanufacturing technologies are already identified (Yang *et al.*, 2018), in some cases demonstrated (Wang, Ong and Nee, 2018) and can be fitted to the product to be remanufactured or the equipment used in the remanufacturing process to optimise EoL decision making (Kerin and Pham, 2019). Interestingly, these identified technologies are not unique to remanufacturing. It is therefore prudent to explore the use of existing manufacturing technology to support remanufacturing activities (Ferrer and Clay Whybark, 2000). The enabling technologies expected to maximise productivity growth include robotics, Additive Manufacturing (AM) methods, integrated with big data analytics, artificial intelligence (AI), sensors and advanced materials (Roos, 2016). These will be surveyed in the next section for applications in remanufacturing.

2.4.1 The Enabling Technologies

The remanufacturing process is made up of many sub-processes including disassembly (All-Party Parliamentary Sustainable Resource Group, 2014) and the development of smart robotic disassembly cells using intelligent sensing and real-time adaptation is identified as a key research topic (Ranky, 2001). It is necessary to recognise disassembly is not simply the reverse of assembly as the product may be worn, fittings may be irreversible, partial disassembly only may be required and destructive operations can be considered (Touzanne, Henrioud and Perrard, 2001). The optimal process varies depending on the product quality and desired outcome. As the application of algorithms in disassembly planning has been extensively reviewed (Wang *et al.*, 2013), this will not be explored in this paper. However, it is worth

noting that their integration with robotics and vision systems can be used to generate and apply disassembly sequences both off-line (ElSayed, Kongar and Surendra, 2010) and on-line (ElSayed *et al.*, 2011). The optimism shown towards the use of robots for EoL product processing waivers over time (Lambert and Gupta, 2004) due to the economies of scale and uncertainties in core quality. However, with the correct evaluation of both the application and the robot's capabilities (Rao, Patel and Parnichkun, 2011, Zheng *et al.*, 2017) robotised disassembly solutions can be realised (Huang *et al.*, 2019).

Once disassembled, AM can be used to restore components (Böß *et al.*, 2017, Yeo, Pepin and Yang, 2017, Abdulrahman, Akinlabi and Mahamood, 2018). Already well documented are the opportunities and limitations (Murmura and Bravi, 2018), key methods and leading providers (Nickels, 2016). However, there is a requirement to better appreciate the environmental implications of hybrid materials and structures, and the impact that customisation and IP of AM parts have on remanufacturing processes (Rejeski, Zhao and Huang, 2018). The design-for-remanufacturing (DfR) methodology for application at a product's beginning-of-life (BoL) could have an interesting sub-method – design-for-AM (DfAM) (Gebisa and Lemu, 2017) supported by demonstration tools to capture and display the different life cycle implications (Müller *et al.*, 2018).

Big data and AI solutions are generally packaged with other technologies for remanufacturing, including data carrying devices and identification labels (RFID, QR etc.) (Zlamparet *et al.*, 2018). Once a core is identified, the remanufacturing process can benefit from an EoL database containing reverse logistics information. This can facilitate the tracking of component quality, quantity and location, and enable the determination of the best facility in which to remanufacture the product minimising environmental impact and optimising resource efficiencies and profits (Wang *et al.*, 2018a). But there is a need for more research in the area

of big data in reverse logistics and cloud-based systems for analysing the data collected on used products and improving the coordination of distributed supply chains (Nguyen *et al.*, 2017). Work has started on developing an understanding of what type of data would benefit remanufacturers using encoding methods to simplify and record materials found in components on RFID tags with (Meng *et al.*, 2016), or without (Nowakowski, 2018), the need to link to databases and decision-making optimisation tools.

Sensors providing in-use real-time big data for manufacturing using data mining models could help explore hidden trends and life cycle knowledge (Zhang *et al.*, 2017, Zhang *et al.*, 2017a). Additionally, virtual Reality (VR) (Fox, 2016) and Augmented Reality (AR) (Kishita *et al.*, 2018) have been recognised as enablers to remanufacturing in a CE for the aggregation and visualisation of information. In the future nothing will be manufactured until it has been designed and refined in cyberspace (Coates, 2000) and the level of 'smartness' of a manufacturing enterprise is determined by the degree to which it has been digitally reflected (Kusiak, 2018). The digital modelling of products or processes is not new but combining the real and virtual worlds and enabling their interaction is. This concept (digital twinning) is generating great and sustainable interest (Lu *et al.*, 2020). Digital twins (DT) fuse real sensors and data (Diez-Olivan *et al.*, 2019) to form representative virtual products or processes. Abramovici, Göbel and Savarino (2017) focus primarily on the re-configuration potential of in-use products using DT but their work also has application in EoL remanufacturing. At the process level, the use of sensor-based tracking to capture real-time data on product manufacturing can support the generation of factory DT (Uhlemann, Lehmann and Steinhilper, 2017), with data-driven simulation deemed suitable for modelling the complexities of remanufacturing operations (Negahban and Smith, 2014, Goodall, Sharpe and West, 2019). These tools are particularly relevant to remanufacturing process design and are therefore

included in the proposed framework [#1, #10]. However, research suggests there a need to further study big data and technology integration in a CE, including remanufacturing (Nguyen *et al.*, 2017), with greater focus on the application of product data captured in previous life cycles on decision-making for future ones (Wang, Ong and Nee, 2018).

Advanced self-healing materials (Wang, Pham and Ji, 2015) and self-maintaining products (Takata *et al.*, 2004) have implications for remanufacturing. They may change the demand, the processes and technology involved expedited by the Materials 4.0 paradigm (Jose and Ramakrishna, 2018). Additionally these may offer improved sensors, systems, cameras and communication interfaces needed for faster data capturing and analysis (both requirements that need to be addressed to realise the technology revolution for remanufacturing (Uhlemann *et al.*, 2017a)).

2.4.2 Integrating and Managing the Technologies

Whilst the technologies involved in manufacturing and remanufacturing may be similar, planning and control in the latter is more complicated due to inherent business variabilities (Guide *et al.*, 2000). The remanufacturer can work to minimise the variability or allow it to exist and install flexible solutions (Huang *et al.*, 2019). Uncertainties in EoL product quality and quantity make disassembly in remanufacturing challenging to automate (Vongbunyong, Vongseela and Sreerattana-aporn, 2017). A high level of certainty of product quality can support confident data-driven decision-making in remanufacturing (Charnley *et al.*, 2019), but if quality or quantity certainty remains low, a collaborative environment where humans, robots and CPS work together could offer a sufficiently flexible solution (Chen, Wegener and Dietrich, 2014, Wegener *et al.*, 2014, Wegener *et al.*, 2015). The smart factory should support more flexible production (Koren *et al.*, 2018), reconfigurability (Koren *et al.*, 2018)) [#2], and differentiated management and control processes (Kagermann *et al.*, 2013). There is a need to

support businesses in the exploration of flexible or reconfigurable factories (Maronati *et al.*, 2018) and processing lines (ElMaraghy and ElMaraghy, 2016) which have the potential to transform traditional linear value streams with well-defined interfaces and clear risks, to matrix-style operations with moving boundaries and evolving opportunities. The "moveable factory" is an interesting alternative, but currently less attractive proposition (Fox and Richardson, 2017). Whatever the overall approach, lessons can be learned from the waste electrical and electronic equipment (WEEE) sector (Li, Barwood and Rahimifard, 2018). Here material recovery solutions involve collaborative cells (Ruggeri *et al.*, 2017), containing vision systems and tool changing capabilities (Wegener *et al.*, 2015), depth sensors for component locating (Bdiwi, Rashid and Putz, 2016), socket changing (Chen, Wegener and Dietrich, 2014) and mobile robots for material relocation (Minca, Filipescu and Voda, 2014). These systems (and others) require the development of suitable software (Salonitis and Stavropoulos, 2013) and production chain-compliance standards (Bonnard *et al.*, 2018, Bonnard *et al.*, 2019) to enable autonomy via information and communications technology (ICT) integration.

The expected growth in ICT comes as no surprise considering the IoT is reliant on the internet to increase the interoperability of people and products. A high-level framework for an ICT infrastructure which is essential for the implementation of circular production systems is proposed by Asif *et al.* (2018) but does not explicitly consider the use of IoT, I4.0 technologies, or how remanufacturing fits. CM with its flexibility and scalability offers a route to facilitate remanufacturing (Fisher *et al.*, 2018) but it is important to ensure good quality of service and security, and resolve issues with network bandwidth, performance, precision and standard communication protocols (Dimitris and Ekaterini, 2016). To optimise CM platforms for on-demand supply, a time-space multi-dimensional optimisation method (Huang *et al.*, 2018) could be used. Equipment control 'as-a-service' (Adamson *et al.*, 2016) is an interesting and

applicable integrated concept that packages resources in a multi-layered CM system using intelligent decision-making modules to control and execute distributed, but cooperating, equipment [#3]. Web-based process planning in decentralised dynamic environments could also be utilised (Wang, 2013) but risks to human safety in these concepts seem to be overlooked.

This section has considered I4.0 technologies in remanufacturing for the CE (summarised in Figure 2-5). Questions remain concerning their autonomy and cooperation (Váncza and Monostori, 2017) so for these concepts to be realised, the systems will need to understand the environment in which they exist and to ensure operator safety, before accepting remotely controlled signals. Assuming the risks can be contained, and the questions resolved, real-time collaborative factories using CM systems can be expected with the integration of machine tools, robots, AM facilities etc. generating process data [#4].

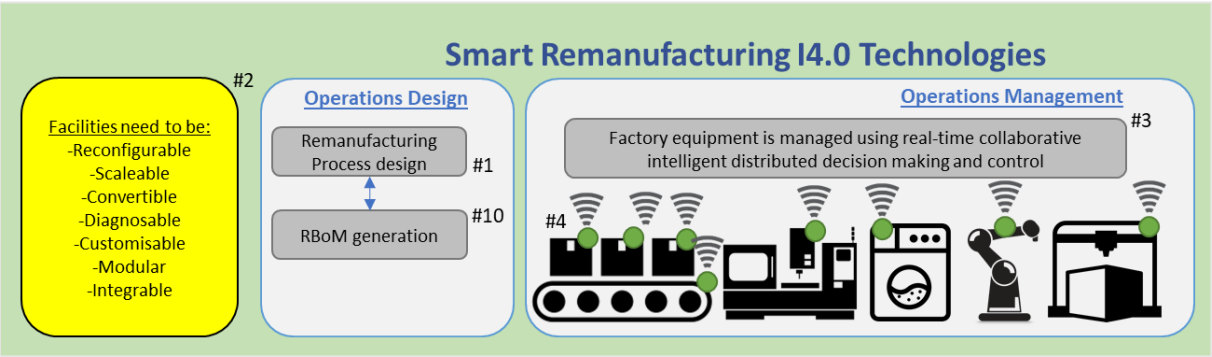


Figure 2-5 Key technology-based findings

2.5 I4.0 for Remanufacturing against the Triple Bottom Line

Sustainable development is supported by balanced economic, social and environmental performance (United Nations, 2005) which is referred to as the triple bottom line (Geissdoerfer *et al.*, 2017). The triple bottom line is utilised in many articles to structure critical, fair and accurate appraisals. Having already covered the enabling technologies this section will expand

to consider their use in remanufacturing for the CE from an economic, social and environmental perspective.

2.5.1 Economic Factors

Findings suggest that the social and environmental benefits of CE business models are relatively clear, but the economic elements including ownership, the cost to customer and producer, and the rebound effects of these models, need to be further explored (Gnoni *et al.*, 2017). For example, utilising I4.0 concepts could improve manufacturing efficiencies, making a product cheaper to purchase. However, without careful consideration of the entire life cycle, this may alter consumption rates (Raihanian Mashhadi and Behdad, 2018), changing the product's remanufacturing potential. Complicating the economic assessment further, limitations have been recognised in popular Life-Cycle Analysis (LCA) techniques to describe a product at the EoL (Boks and Stevels, 2007) and for meeting the needs of emerging smart supply chains. The use of real product data to generate more accurate assessments (Raihanian Mashhadi and Behdad, 2018) through adapting EoL strategy tools (Cerri and Terzi, 2016) or performing real-time LCA (Jensen and Remmen, 2017), would be beneficial. However, the main economic themes identified from this review relate to the opportunities that exist in the relationships remanufacturing has with businesses that are transitioning to more product-service models, and how they harness the benefits of newly available product data streams.

2.5.1.1 Shifting Business Demands

To move towards a CE, different business models are required where manufacturers sell services to support a combination of high quality long-lasting and short-lived durable products (Esmaeilian, Behdad and Wang, 2016). There have been several terms given to models that provision services with products (Li and Found, 2017) but the most popular model identified from this review is "Product-Service-Systems" (PSS). In PSS, the supplier retains ownership

of the product and leases it to the user. This prompts the owner to squeeze value out of the product for as long as it is economically viable, utilising repair and service strategies to achieve multiple life cycles, which could benefit the remanufacturing industry by providing a steady supply and demand. Remanufacturing businesses will have to adapt should their supplier or customer pursue a new PSS model as product design may be modified to assist with "servitisation" for efficient and effective service delivery. These design modifications may vary between a product intended for remanufacturing or for maintenance. This, in turn, influences remanufactured part processing, demand and opportunities. Different PSS types can enable a number of CE strategies (de Pádua Pieroni *et al.*, 2018) and real case studies can be used to illustrate the benefits of employing digital technology in this arrangement (Bressanelli, Perona and Saccani, 2017, Lindström, 2017, Bressanelli *et al.*, 2018). Current research into circular businesses suggest that PSS-orientated and remanufacturing-based models are particularly common archetypes (Rosa, Sassanelli and Terzi, 2019) yet there is a lack of large-scale quantitative studies suggesting this field is still in its infancy (Xin, Ojanen and Huiskonen, 2017) .

Remanufacturing is a key element of circular production, promoted in scenarios where people share and lease assets (Kishita *et al.*, 2018). Sharing or leasing will necessitate a change in manufacturing focus towards products with increased desirability, reliability, durability, serviceability, standardisation [#13] and design for disassembly, re-assembly and EoL waste minimisation. These are all made more attractive if ownership is retained and the commodity is managed using IoT technology in 'pay-per-performance' (Bressanelli, Perona and Saccani, 2017) or 'pay-per-use' (Heiko, Mirella and Jennings, 2017) models with the product-service configuration made specific to the business (Senzi *et al.*, 2016), aligning with its asset recovery strategies and value proposition. Whilst there is interest in moving towards PSS business

models to support sustainability, some researchers question the desire, risk and capabilities of industry to transition successfully. Currently, essential data management facilities are insufficient (Mert *et al.*, 2016) and new methods and competences are needed to implement PSS operationally (Stark *et al.*, 2014). However, advances in these areas are likely with rapid progress being made in the application and reliability of big data analytics and AI. More complicated to predict is whether sustainability can be achieved if the PSS model being employed is not originally designed with sustainability in mind (Pieroni *et al.*, 2017), as PSS demand a significant shift in society and business organisation. Despite these concerns, PSS provisions are assumed to increase and are reflected in the framework alongside the traditional MoL "with customer" user state [#12].

2.5.1.2 Extracting Value from New Data Streams

I4.0 technologies can enable measurement capturing for factories of the future (Muñoz-Villamizar *et al.*, 2018), with the potential to facilitate their reporting (Friedemann *et al.*, 2016) [#14]. Traditional GDP indicators can be enhanced to include environmental, social and political elements to enable the transformation and tracking of organisations towards sustainable CE business models (Lukman *et al.*, 2016) using I4.0 facilities. Existing critical success factors (CSF) can be useful in understanding how I4.0 works with environmentally-sustainable manufacturing (de Sousa Jabbour *et al.*, 2018) but whatever the metrics, remanufacturing reporting will likely require product [#16], process [#17], business [#18] and logistics data [#19] to feed new internal and external decision-making systems. Captured data can be used to support purchasing and pricing, plant location, design, logistics and inventory decisions (Viet, Behdani and Bloemhof, 2018), all integral to the acquisition of used products (cores), the first step in the remanufacturing system (Xie *et al.*, 2015). Without cores and a demand for products, remanufacturing is economically impracticable. Disruption and

uncertainty in material supply is an issue for any business (Gaustad *et al.*, 2017) and is particularly prevalent in remanufacturing (Guide *et al.*, 2000). As IoT can digitally link the supplier and customer [#12] (Man and Strandhagen, 2017), it may support core acquisition [#6] (Abubaker *et al.*, 2017) with greater visibility of availability and quality. Through combining product nominal data (e.g. design specification information) [#7] with performance [#8] and product status data [#9], it may be possible to reduce risks and increase efficient resource circulation [5] (Matsuyama, Fukushige and Umeda, 2015). For example, the profile of the first generation of returned cores can be used to support the planning, and provide components, for the manufacture of the second [#1]. However, linking the different generations demands smart BoM (and related Bill of Process) management. To do this, it may be possible to transform a static BoM into a remanufacturing BoM (rBoM) [#10] using the process designed by Zhou *et al.* (2018) that builds service BoMs for complex, variable products, representative of remanufacturing cores.

The emerging technologies discussed above are capable of facilitating the process of value co-creation and environmental sustainability along the value chain for PSS stakeholders (Li and Found, 2017), strengthened by the operational data made available from CPS (Herterich, Uebernickel and Brenner, 2015). This data, now a commodity, can be sold to service providers including remanufacturing firms [#11] (Romero and Noran, 2017). There are benefits to be had from the sharing of knowledge between producers and users. These include financial gains from longer-term relationships with the user providing access to product utilisation information for further exploitation (Wellsandt and Thoben, 2016). The diversification potential of a service offering depends on the data received when the product is with the customer, either owned or leased [#12]. However, the unwillingness of users to participate in the collection of data along with the role that they play in generating and sharing it, is still a concern (Field *et al.*, 2018).

Nevertheless, if the provider remains the product owner and the partnership relies on availability (Mert *et al.*, 2016), it will be possible to retrieve valuable information about in-use performance and surrounding influences (Abramovici *et al.*, 2016).

This sub-section has explored the economic factors (summarised in Figure 2-6). The impact of I4.0 on a product's life cycle needs to be further investigated as its application may affect opportunities and profitability by changing the product's potential, likelihood and desirability to be remanufactured. The effects of I4.0 on the remanufacturing supply chain, changing product ownership and PSS are popular research topics but true economic benefits will only become evident once real-life applications have materialised. As the implementation of I4.0 is likely to be progressive and part of a continuous improvement activity, it may not be possible to assess its impact for some time.

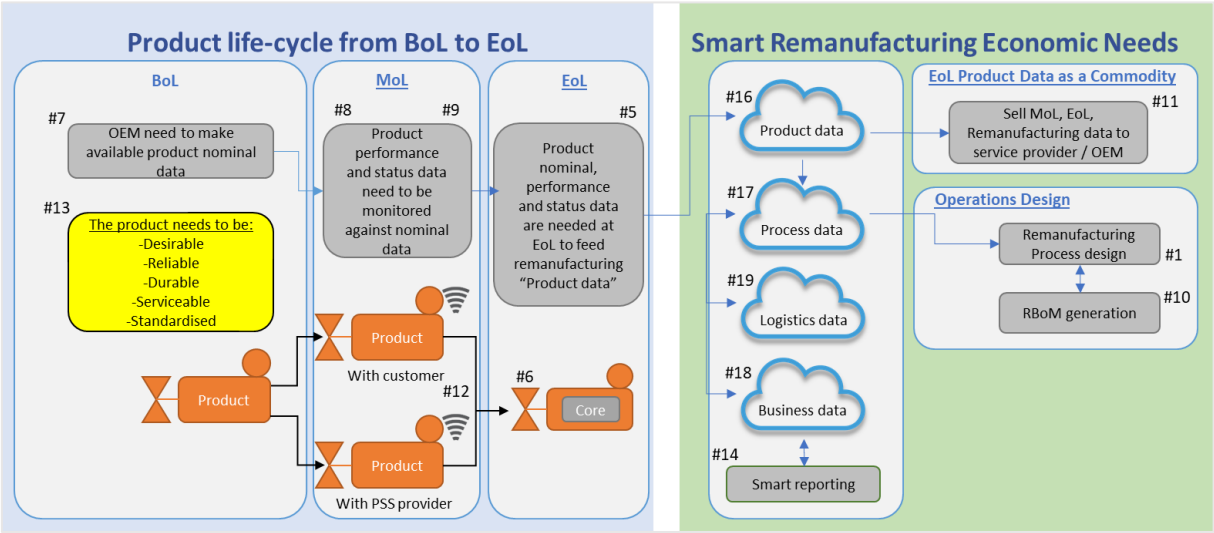


Figure 2-6 Key economic findings

2.5.2 Social Factors

"In an increasingly complex society as well as increasingly complex manufacturing value networks, most of the challenges cannot be faced by science and technology alone" (Bueno, Girot and Gutiérrez-Orrantia, 2017). There is a need to consider human behaviours, social

interactions, trends, emotions, relationships and interfaces between businesses, stakeholders and CPS. There are two emerging types of business visionaries in this area [#20]. The "ecopreneur" focuses on resolving environmental problems whilst creating economic value, whereas the "sustainable entrepreneur" resolves social and environmental problems through managing sustainable businesses (Carvalho *et al.*, 2018). However, vision alone cannot realise I4.0, and there is a real need for a digitally skilled workforce. The lack of this is preventing investment in I4.0 technologies (Institution of Mechanical Engineers, 2018) with training of engineers and operators on the benefits of CPS, and the attributes to develop and maintain them, representing one of the major barriers to adoption (Dimitris and Ekaterini, 2016).

2.5.2.1 Workforce Capabilities

Alignment of remanufacturing skills with those required for the high-value product manufacturing sector may be advantageous as there are lower volumes and greater variability in product build specifications here, than in mass manufacture. Greater consideration needs to be given to both physical and cognitive ergonomics in factories since IoT will promote more CPS-human collaborative work environments [#21] (Siemieniuch, Sinclair and Henshaw, 2015). Safety will be critical, and processes will generate vast data sets, some of which will need to be human readable and understandable (Müller *et al.*, 2018). IoT will enable autonomous decision-making in MoL in-use products that will affect EoL opportunities. However, the level of human involvement, and the extent to which the human can override or be controlled by autonomous decisions, need to be established and customised to best suit the application and risk (Shu *et al.*, 2017).

Managers have been identified as the most essential actors for integrating the use of I4.0 to achieve sustainability (Chauhan, Sharma and Singh, 2019). Should they decide to exploit these technologies along with collaborative human-machine working, there would be a need to

prepare employees to better understand risks and opportunities (Birkel *et al.*, 2019) with benefits in integration and workplace enrichment expected (Stock *et al.*, 2018). Skills transfer is not one-way with human-to-robot disassembly training also explored (Vongbunyong, Vongseela and Sreerattana-aporn, 2017). However, most applicable articles that target training are for human operatives using I4.0 technologies including VR (Müller *et al.*, 2016a) or AR (Müller *et al.*, 2016b) systems, and mock products fabricated using AM techniques (Menn *et al.*, 2017, Menn *et al.*, 2018). VR allows users to view computer-generated 3D components, systems or environments. AR can be employed to superimpose computer-generated graphics over real-world components, systems or environments, and AM can be used to build genuine or prototype products. Early indications suggest these tools can benefit training but there are still barriers to implementation including initial equipment purchasing costs, poor portability and frequency of errors (Menn, Ulbrich and Seliger, 2018a). Time is likely to change this with the exposure of I4.0 technologies to engineers and operators being instrumental to understanding and developing their capabilities, which justifies their inclusion in the framework [#22].

2.5.2.2 Changing Societal Demands

New technologies, including VR and AR, will change the expectations of customers, partners, and employees in a continually adapting digital future (Craig, 2017). Similarly, the increasing desire for customised and personalised products will impact manufacturing system design, planning and operation (Hu *et al.*, 2011). As a result future remanufacturing systems need to be able to deal with a higher level of variety, best managed when a product is first designed with it in mind (Kuo and Smith, 2018). A key area of research in need of exploration is the connection between business models and design-for-remanufacturing strategies (Esmaeilian, Behdad and Wang, 2016). Whilst there is no work identified from this search that explores this

connection, applicable Design-for-Disassembly (DfD), Design-for-Service (DfS), Design-for-Sustainability (D4S) and DfR strategies have been summarised (Chang, Ong and Nee, 2017a). Adopting smart interface design concepts with tools to evaluate adaptability (Gu, Hashemian and Nee, 2004), or open-architecture products, modular in structure allowing design input from the end user (Koren *et al.*, 2013) could help engineers future-proof and prepare EoL strategies for remanufacturing. "Designing-in" extension to product life cycle features, and improving the predictability of upgrade windows and EoL product retirement is a feasible approach (Erler and Rieger, 2016). These considerations at BoL have implications on the ease and profitability of remanufacturing [#23].

Whatever the business approach, companies who engage in advanced manufacturing practices at the operations level do not necessarily participate in environmental management at the tactical or strategic levels (Muñoz-Villamizar *et al.*, 2018). However, this statement is based on one article that focuses only on Small-Medium Enterprises (SMEs) in Spain. Notably, much of the research in this area is undertaken in developed countries. The relationships between the different business levels in SMEs to large corporations around the world should be further explored (Müller and Voigt, 2018). On this, several articles highlight that there are numerous and complex economic and social challenges in the implementation of sustainable strategies in developing or newly industrialised countries (Singhal *et al.*, 2018, Szalavetz, 2018, Wakjira, Altenbach and Ramulu, 2018). A key trend in these papers is the recognition that literacy and general awareness of sustainability are barriers to implementation (Ibrahim, 2017). It is therefore necessary to consider the impact of global cultural differences on remanufacturing as more of the world becomes technologically advanced.

This sub-section has considered the social factors (summarised in Figure 2-7). The social impacts of I4.0 in remanufacturing are much the same as in other IoT application areas (e.g.

Energy and Healthcare) where the skills, attributes and behaviours of the humans involved will change. Some of the emerging technologies can be utilised in training and design to encourage consideration of a product's EoL at the BoL stage, but people must first recognise the importance of sustainability and the benefits of IoT to make progress. Furthermore, ideas spawned in developed countries need to suit conditions in those still developing, as the I4.0 infrastructure of the future is global. The proposed framework contains reference to VR and AR in training, and sustainable manufacturing and entrepreneurship as an attribute of the I4.0 remanufacturing workforce.

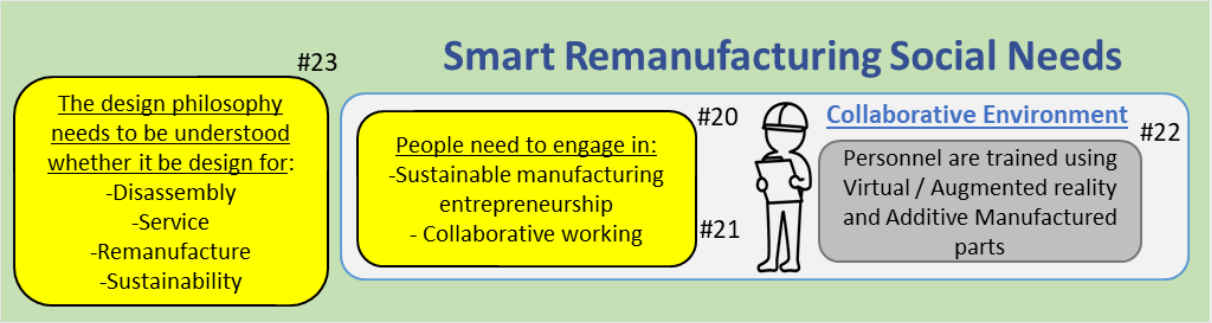


Figure 2-7 Key social findings

2.5.3 Environmental Factors

There were few articles related to this section, yet their quality and contribution were significant. "Nature has been and is supplying the necessary resources for men and technology's life cycles as well as absorbing and metabolizing related waste" (Jovane, Seliger and Stock, 2017). Whilst, I4.0 can permit the efficient allocation of resources using real-time data from production systems and the supply chain (de Sousa Jabbour *et al.*, 2018), its ability to bring habitual sustainable manufacturing practices to fruition is highly dependent on the digitalisation of existing technologies (Carvalho *et al.*, 2018). However, I4.0 alone does not explicitly tackle sustainability in manufacturing (Man and Strandhagen, 2017) so regulations and standards are being used to drive it.

2.5.3.1 Regulations and Standards

Directive 2009/125/EC (European Council, 2009) establishes a framework for the setting of standards for nations to structure policies to encourage manufacturers to consider a product's environmental life-cycle impact at the design stage. At this stage, there is the greatest opportunity to facilitate efficient use of resources integrating the requirements into CE marking and the declaration of conformity certification process. BS ISO 8887-1:2017 (British Standards Institution, 2017) specifies requirements for the content and structure of technical documentation at the design stage as compulsory output deliverables to include information on manufacturing and EoL processing of products through potentially multiple life cycles focusing on minimising environmental impact. It also demands the archiving of information on assembly methods and batch sizes, test certificates and results, previous life cycles and EoL decisions. These standards will influence the remanufacturing industry [#24], customer attitudes towards remanufactured components, information availability and product remanufacturability, all of which contribute to changes in consumption.

2.5.3.2 Green Demands

Boks and Stevels (2007) stress that general principles have little value unless made specific to the context in which they will be used. In their thought-provoking article, they evaluate the impact of green principles using real examples and suggest the perception of what is green depends on the values that different stakeholders hold. Rethinking a product as a dynamic evolving set of characteristics or qualities, rather than static entities, could create new opportunities [#26]. As companies utilise the I4.0 technologies to gather MoL data, they can better understand usage patterns and configure offerings to suit different customers in a much finer-grained fashion (Spring and Araujo, 2017). With this new dynamic set of characteristics, the way that products are identified and valued may change. 'New' and 'remanufactured'

products may not be differentiated if they meet the users expectation and the specified functionality (Tolio *et al.*, 2017) [#27]. With this, the smart circular factory could perform manufacturing and remanufacturing operations, smoothing product variability, with minimal environmental load. However, the product is not the only consumer of natural resources in the remanufacturing supply chain. The factories themselves also need to be considered. Monitoring factory assets to reduce resource consumption (Peralta Álvarez, Marcos Bárcena and Aguayo González, 2017) and using lighter weight AM components for products or remanufacturing equipment can cut emissions (Abdulrahman, Akinlabi and Mahamood, 2018) and thus the impact of the remanufacturing business on the environment. Looking further afield, Byrne *et al.* (2018) present an interesting paper that reviews biologicalisation and provides recommendations on the integration of biology or biologically inspired concepts into applicable methods and models, CPS, digitalisation and I4.0 [#25]. Exploring nature and the relationships between science, technology and sustainability, Healy (1995) warn of the over reliance of technology to resolve issues in the environment that have themselves been caused by technology. He proposes a realignment of science, technology and politics with the idea of being 'in' instead of 'managing' nature and presents 'metascience' as a more flexible all-encompassing subject over 'black-boxed' engineering that currently encourages boundaries, assumptions and a narrowing of vision, and therefore ignores external implications.

This sub-section has collated the findings related to environmental factors. Research in the area is fragmented but interesting. Little work is being conducted on the subject and what has been undertaken is either bundled under the general manufacturing umbrella or touched on at such a high level that it is ambiguous. However, there is widespread recognition that the depletion of the earth's natural resources must stop, and many researchers state that deploying I4.0 and IoT technologies in remanufacturing could be environmentally helpful. Standards aimed at the

manufacturing industry can apply in part, so too the concepts of biologicalisation, the perception of "green" and the acceptance of remanufactured parts back into the supply chain. These have been included as overriding factors in the research framework as real focus on the environmental impacts of I4.0 on the remanufacturing field is lacking.

2.6 Framework and Agenda for I4.0 in Remanufacturing

As mentioned in Section 2.1, 329 articles from a systematic database search were identified as being relevant to I4.0 in remanufacturing for the CE. Most of the technologies within remanufacturing already exist within the manufacturing space but a gap was identified in the literature on smart technologies for the CE specifically in remanufacturing. To fill this gap, a review has been conducted to describes current trends before looking at how I4.0 for remanufacturing can influence or be influenced by economics, society and the environment. The key findings, referenced throughout this article as [#X], are listed in Table 2-2 together with other conclusions as research hypotheses. They contribute to the development of Figure 2-8 which presents a framework for I4.0 in remanufacturing for the CE (arrows represent the flow of the physical product or associated data in a smart remanufacturing environment and the yellow boxes represent key enablers). Section 2.6.2 then sets out the research agenda. The framework should provide industry with a vision of the smart remanufacturing future, whist the agenda should offer scholars a summary of the major topics and potential research directions.

2.6.1 Framework

At BoL, the product needs to be designed with the most applicable philosophy whether it be DfD or DfR, etc. [#23]. It should be durable and serviceable to extend its life expectancy, but also standardised to support automated EoL processing [#13]. Product nominal data [#7], made available at BoL, should feed into MoL data, influencing both MoL performance [#8] and status

data [#9], all useful to future product design [#31] and service provisioning (internal or external) [#28]. The data stream ends up as EoL data [#5], available to sell as a commodity [#11]. Whilst with the customer (potentially leased from a PSS provider [#12]), the product should be connected to the IoT, supplying MoL data such as operating and environmental parameters. Gaps in data should be filled utilising AI techniques to provide transparency and comparability of product condition, remaining life and failure trends [#29]. This big data can be extrapolated to support remanufacturing process management but the effect of poor or incomplete data on subsequent decision-making and throughput needs to be appreciated (Okorie *et al.*, 2018a).

The nature of remanufacturing products with variable quality calls for a flexible, potentially cyclic revision of process redesign [#1, #10] dependent on core attributes and desired outcome (complete, partial, targeted or destructive disassembly etc.) [#6]. Using AI to plan, schedule and optimise, remanufacturing process design [#30] can influence, and be influenced by, decisions made in the logistics data space, where AI supports management of resources and pricing takes place in a cloud-based system [#15, #19]. The product's unique ID [#16] is utilised throughout remanufacturing to interface with the BoL-EoL data streams and to track remanufacturing progress [#17].

Process design distributes intelligent decision-making on the operations that can / need to be completed. These cover the allocation of resources, potentially across multiple facilities [#33], and the tracking of progress in real-time against the schedule to optimise profitability [#18]. Networked machines, CPS, robots and products provide real-time operational data for reporting metrics, in reconfigurable, modular factory environments [#3]. Product [#16], process [#17] and business data [#18] are managed using CM methods that are scaleable, providing sufficient bandwidth, performance and security [#32]. (There are general requirements to define data structures and compatibility, security, scalability and resource consumption of IoT technology

throughout the value network, to use big data, machine learning and AI. However, these are not unique to remanufacturing and will likely affect other sectors more (e.g. healthcare or banking) forcing the development of suitable transferable solutions.) AI systems fill voids in product and operational information and consider the data obtained during MoL to observe patterns in customer behaviours relating to product condition [#29].

Flexible, reconfigurable facilities [#2] are supported by operators, maintenance technicians and engineering teams that are trained in CPS [#22], human-machine interoperability [#21] and sustainable manufacturing methodologies [#20] facilitated by I4.0 technologies [#4]. Business metrics are reported using new CSF [#14], lessons learned can be shared with OEMs, and closer relationships can be formed between the user, customer, PSS provider and remanufacturer.

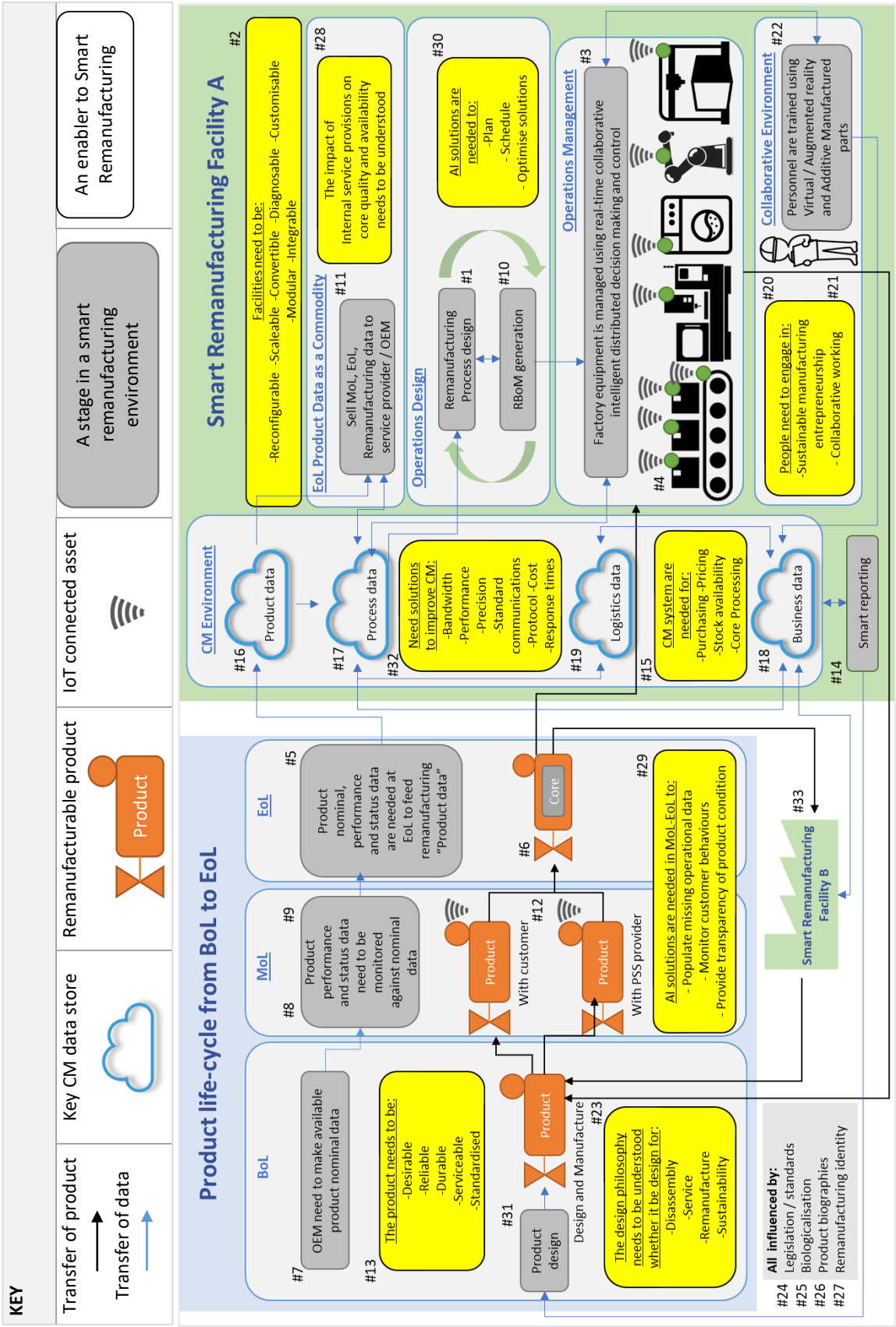


Figure 2-8 Proposed framework for I4.0 in remanufacturing for the CE

Table 2-2 Research Hypotheses

#	Review findings as hypotheses for Smart Remanufacturing research
1	Smart remanufacturing process design uses logistics data, discrete event simulation, with real-time AI planning, control and decision-making tools.
2	Characteristics of a smart reconfigurable remanufacturing system include scalability, convertibility, diagnosability, customisation, modularity and integrability.
3	A smart remanufacturing facility utilises intelligent and distributed decision-making modules to control and execute distributed, but cooperating, shop-floor equipment.
4	Web-based distributed process planning in a decentralised dynamic environment supports real-time collaborative factories using CM systems.
5	The product at EoL (with customer or PSS) provides the core for remanufacturing and the information for EoL processing.
6	The IoT is used to support core acquisition and inform and trigger reverse logistics activities.
7	BoL product nominal data provide information on the original design and manufacturing parameters.
8	MoL product performance data provide information on the quality of the product and its service history.
9	MoL product status data provide information on life expectancy.
10	Linking the EoL of one product generation to the production of the next generation demands smart BoM management and is dependent on smart remanufacturing process design.
11	CPSs provide a product's MoL data to sell as a commodity to service providers including remanufacturers.
12	MoL data can enhance the knowledge shared between producers and users when the product is with the customer, either owned or leased.
13	Product sharing or leasing necessitates a change in manufacturing focus towards products with increased desirability, reliability, durability, serviceability and standardisation.
14	I4.0 technologies are enablers of measurement capturing and reporting in smart remanufacturing.
15	In smart remanufacturing, data are used to support supply chain inventory decisions, plant location and design, logistics, purchasing and pricing.
16	Smart remanufacturing reporting requires product data managed using CM methods supplied at EoL.
17	Smart remanufacturing reporting requires process data, relevant to the process design, managed using CM methods.
18	Smart remanufacturing reporting requires business data managed using CM methods.
19	Smart remanufacturing reporting requires logistics data managed using CM methods.
20	Environmentally conscious business visionaries and managers facilitate sustainable remanufacturing.
21	Physical and cognitive ergonomics must be considered as IoT will promote greater CPS-human collaborative work environments.
22	The exposure of engineers and operators to I4.0 technologies promotes their application.
23	The design philosophy adopted at BoL influences ease of EoL disassembly, remanufacturability and profit margins.
24	Legislation and standards applied to the product to be remanufactured or the remanufacturing industry directly impact resource consumption.
25	Nature-inspired concepts can be integrated with CPS, digitalisation and I4.0 technologies in smart remanufacturing.
26	The IoT can be used to build product 'biographies', opening up new business opportunities arising from owning, controlling and integrating the generated data streams.
27	New products and remanufactured products are not differentiated if they meet the customer's expectation and the specified functionality.
28	Internal and external services make use of MoL data that provide information on core availability and remanufacturing opportunities.
29	During MoL, products are connected to the IoT, with AI techniques employed to fill gaps in data and to provide transparency and comparability of product condition, remaining life and failure trends.
30	AI techniques are used in planning, scheduling and optimising remanufacturing process design which influences, and is influenced by, decisions made in the logistics data space.
31	The availability of BoL from the OEM, MoL data from the connected product and EoL data from remanufacturing helps future product design.
32	CM methods that are scaleable, with suitable bandwidth, performance and security benefit the variable resource consumption associated with remanufacturing.
33	Distributed intelligent decision-making is utilised for the allocation of resources, across multiple facilities, and the tracking of progress in real-time against the schedule to optimise profitability.

2.6.2 Research Agenda

From the framework some key recommendations for further work can be proposed. For researchers, the main themes are identified in Table 2-3.

Table 2-3 Research Agenda for Smart Remanufacturing

	Brief Definition	Research Agenda	
Technology	Smart remanufacturing assumes the utilisation of I4.0 technologies on the product to be remanufactured as well as the remanufacturing processing equipment and business management systems.	Product	Investigate the remanufacturing functions that are affected by product quantity and quality that could benefit from data supplied by I4.0 technologies Evaluate the sustainable benefits of the technology on these functions using real world applications Identify the data requirements from existing products to enable intelligent future life-cycle decision-making
		Process	Explore the integration of I4.0 technologies to develop flexibly managed remanufacturing process Develop AI decision-making solutions to support remanufacturing planning, control and execution Evaluate factory digital twins for simulating potential process outcomes based on inbound product knowledge
		Management	Explore how autonomous decision-making in MoL in-use products could generate/influence EoL remanufacturing opportunities Analyse management metrics and evaluate benefits of real-time data input Identify, invest and support the technical team implement I4.0 technologies in processes that they already understand to encourage the exploration of I4.0 in real applications
Economic	Engagement with both traditional and PSS business models will be needed simultaneously whilst the emergence of new data streams will offer alternative / more efficient value streams.		Investigate and analyse mechanisms to facilitate the optimisation of remanufacturing businesses within, or alongside PSS structures Identify key remanufacturing business metrics that can be enhanced with near real-time data input Explore the economic benefit of investing in systems that can extract historical or MoL data from products to sell back to the OEM
Social	Smart remanufacturing systems will be developed and maintained by specialists in CPS, HMC with an appreciation of evolving global cultural differences and challenges.		Investigate the skillsets of workers in the high-value product manufacturing sector for cross referencing with the manufacturing sector Demonstrate more HMC/HRC and flexible facilities on real remanufacturing case studies Inquire into the psychology of society to accept 'new' and 'remanufactured' products as equal
Environmental	The smart remanufacturing industry can influence and be affected by government policies aimed at sustainable development.		Explore environmental implications of hybrid materials and structures on remanufacturing processes Further consider the integration of nature inspired concepts into applicable smart remanufacturing methods and models

When pursuing any of these suggestions, scholars must remain conscious of the need to ensure future remanufacturing aligns with CE and sustainable development principles. For industry-base readers, the framework could be used to identify a process to trial the implementation of I4.0 technologies. This will support workforce development and provide a real environment to explore capabilities, interfaces and benefits.

This work does have limitations and can be further developed. The initial article search used specific keywords in English that could be adapted or expanded. The framework could be presented to stakeholders and/or interrogated further. Real case-studies from developed and developing countries could be overlaid to explore trends, gaps and social challenges. However, the next steps should include the exploration of the themes in Table 2-3 along with the development of a strategic time-based roadmap specific to a remanufacturing business to encourage adoption from quantitative, real-world studies prioritised accordingly.

2.7 Concluding Remarks

The contribution of this article is twofold. First, it presents the findings of a systematic review of the published literature on Smart Remanufacturing with respect to the triple bottom line. Second, it builds a framework and research agenda from the findings, identifying relationships and gaps that can be explored in the future.

There are many frameworks that encourage discussions on I4.0 in manufacturing, with far fewer in remanufacturing. Those frameworks addressing remanufacturing present a vision of new business models, an increase in PSS structures, greater automation with digitalised links between customers and suppliers and a change in skill sets. As remanufacturing relies on

suppliers for cores and customers for sales, remanufacturers will also need to adapt and digitalise to remain competitive.

Future work needs to be aimed at developing, and demonstrating, in real remanufacturing applications, the relationships and interfaces, methods and protocols that link the key findings. The impact on changing remanufactured product ownership should be explored as this may influence the service and support structure of stakeholder organisations. The expansion of PSS encourages the exploitation of MoL data to provide users with enhanced support, service and EoL decision-making. PSS may drive OEMs to consider D4S, which will impact remanufacturability depending on their approach (to support maintenance, service, remanufacturing or disposal etc.). How these models affect remanufacturing remains to be seen. However, what is evident is that there are opportunities to use the MoL data to understand failure modes and extrapolate life expectancy (Ondemir and Gupta, 2014). This is potentially useful information to remanufacturers should they be able to adapt their processes accordingly to take full advantage of the data. This concept should be further explored as there is currently little evidence to suggest that remanufacturers would change their processes based on the availability of MoL information alone.

Business models will need to be adapted to consider an increase in robotics, automation, CPS and the integration of ICT with big data analytics, machine learning, AI and decision-making capability. These technologies will affect both manufacturing and remanufacturing in the short term. At the shop-floor level, the use of I4.0 technologies could allow for greater product and process information availability, but the accuracy, timeliness, and completeness of the data need to be managed appropriately. New measurements and critical success factors are likely to be required to track progression towards sustainability that may or may not align with those developed for manufacturing. At the same time, the adoption of synthetic biology-based

processes and the diffusion of capabilities enabling the creation of advanced materials (Roos, 2016), represent potential medium to long-term developments.

I4.0 will bring the end-to-end value chain stakeholders closer together, with IoT transforming their relationships from a linear to a networked multi-level one, and remanufacturing businesses will have to respond to this. Flexibility is key, with the concept of reconfigurable remanufacturing CPS utilising cloud-based IT systems providing a vision of the future.

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2.9 Published Material Notes and Linking Section

The following information should help the reader understand the link between Chapters 2 and 3 and expands on material that was not published, but deemed relevant, by the author or examiners.

2.9.1 Notes

There continues to be conflicting views regarding the selection and classification of the core technologies that can be called 'smart' as discussed by Kang et al. (2016) and Kusiak (2018). What makes the system smart is the integrated, collaborative, real-time response of the solution to meet changing demands and conditions. However, for clarity, the main technologies that are considered smart (as aligned with Mittal et. al (2018)) for this research are -

- *Augmented Reality (AR) and Virtual Reality (VR)*
- *Additive Manufacturing*
- *Internet of Things*
- *Big Data Analytics*
- *Cyber-Physical Systems*

Section 2.4.1 paragraph 2 briefly discusses additive manufacturing (AM) and its role in repairing worn components as part of the remanufacturing process. There are a number of methods that can be used but a popular one in remanufacturing involves depositing metal onto a worn surface before re-machining the material back to the original shape / surface properties. Laser metal deposition is discussed by Abdulrahman, Akinlabi and Mahamood (2018) and Yeo, Pepin and Yang (2017) who also explore high pressure low spray techniques.

With regards to remanufacturing industry best practices, Chapman et al. (2010) provide a comprehensive assessment within the UK. Locally, Caterpillar Inc. is recognised as a major player, and as they contribute to research into remanufacturing at the university, one of their main sectors, large off-highway engines, will form the focus of the cases studies going forward.

2.9.2 Linking Section

Table 2.2 is an output of the research so far. It provides a list of possible hypothesis that may be examined based on the findings of the review. A number of these hypothesis have had to be assumed to be true in order to address the knowledge gaps in the areas identified in the research agenda (Table 2-3). These are -

- *#5 The product at EoL (with customer or PSS) provides the core for remanufacturing and the information for EoL processing.*
- *#6 The IoT is used to support core acquisition and inform and trigger reverse logistics activities.*
- *#7 BoL product nominal data provides information on the original design and manufacturing parameters*
- *#8 MoL product performance data provides information on the quality of the product and its service history*
- *#9 MoL product status data provides information on life expectancy*
- *#14 I4.0 technologies are enablers of measurement capturing and reporting in smart manufacturing.*
- *#28 Internal and external services make use of MoL data that provide information on core availability and remanufacturing opportunities.*

These assumptions are taken forward into chapter 3 and chapter 4 along with a selection of elements from the research agenda. The agenda items that have been selected relate to 'Technology' and include all of those that belonging to the 'Product' including –

- *Investigate the remanufacturing functions that are affected by product quantity and quality that could benefit from data supplied by I4.0 technologies,*
- *Evaluate the sustainable benefits of the technology on these functions using real world applications,*
- *Identify the data requirements from existing products to enable intelligent future life-cycle decision-making,*

as well as the requirements to 'develop AI decision-making solutions to support remanufacturing planning, control and execution' and 'explore how autonomous decision-making in MoL in-use products could generate/influence EoL remanufacturing opportunities' from 'Process', and 'Management', respectively.

3 EMERGING I4.0 TECHNOLOGY IN REMANUFACTURING

A REVIEW OF EMERGING INDUSTRY 4.0 TECHNOLOGIES IN REMANUFACTURING

Published review.

Mairi Kerin†, Duc Truong Pham†

(2019) "A review of emerging industry 4.0 technologies in remanufacturing", *Journal of Cleaner Production*, Vol. 237 pp. 117805. https://doi.org/10.1016/j.jclepro.2019.117805

M.K. Conceived and designed the review, performed the analysis, interpreted the data, and wrote the manuscript. D.T.P. supervised the work, supported the execution and interpretation of the findings, critiqued, and edited the manuscript and advised on the journal to which the article would be submitted.

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3.1 Abstract

This paper reviews the literature on the emerging digital technologies of Industry 4.0 (I4.0) focussed on the applicability of the Internet of Things (IoT), Virtual Reality (VR) and Augmented Reality (AR) in remanufacturing. Inspired by the frameworks developed to support exploration and realisation of I4.0 technologies for disassembly, the paper discusses the same emerging technologies in the wider context of remanufacturing. Trends and gaps have been identified from a value-creation perspective that encompasses the product to be remanufactured, the remanufacturing equipment and processes adopted and related organisation issues. Findings suggest there is a need to explore the connection of cyber-physical systems to the IoT to support smart remanufacturing, whilst aligning with evolving information and communication infrastructures and circular economy business models. The review highlights twenty-nine research topics that require attention to support this field.

3.2 Introduction

Remanufacturing is an important part of a circular economy. Through the remanufacturing of products, there are opportunities to increase the efficiencies of resources, reduce waste and support cleaner, more sustainable production, as demonstrated by Liu *et al.* (2014). Ijomah *et al.* (2007) provided a thorough review of the environmental and financial impact of increasing waste streams and influencing legislation, summarising case studies across the UK's manufacturing sectors evaluating the state of industry with respect to remanufacturing attitudes.

The definition of remanufacturing varies amongst industries. However, BS 8887-220:2010 is generally accepted with remanufacturing being the "steps required to change the product into as-new with at least equivalent performance and warranty of new" (British Standards Institution, 2010). This is the definition that will be adopted throughout this review. A key

activity in remanufacturing is disassembly, reviewed by Chang, Ong and Nee (2017a) who identified relevant emerging digital technologies including the Internet of Things (IoT), Virtual Reality (VR) and Augmented Reality (AR).

This state-of-the-art review identifies that there are no articles specifically exploring emerging I4.0 technologies in remanufacturing. Wenjie *et al.* (2016) did publish an article titled "Remanufacturing in Industry 4.0" but their work was high-level, comparing I4.0 with blood circulation systems and citing only three other research papers. In contrast, Alcácer and Cruz-Machado (2019) provide an extensive review of the literature before setting out a road-map for I4.0 fulfilment in the manufacturing sector. However, this review is specific to manufacturing, referring to remanufacturing only once. Additionally, the roadmap is completed to the conceptual level only and does not propose an extensive list of research topics as the present review does. Similar in depth but from a big data analytics perspective, the article by Ren *et al.* (2019) offers a comprehensive review into smart manufacturing and a product's lifecycle, before coining the term 'sustainable smart manufacturing' that includes remanufacturing but is not exclusive to it. In contrast, this review aims to fill a specific gap, that of the provision of research questions to allow a logical approach to applying I4.0 to remanufacturing.

The digital transformation enabled by the emerging digital technologies is known as Smart Manufacturing or Industry 4.0 (I4.0), referred to within this text as I4.0. It is related to developments in cyber-physical systems (CPS) building on the three previous revolutions pertaining to mechanisation, electrification and information technology. CPS are mechanisms that are controlled or monitored by software integrating computers, networks and physical processes (Khaitan and McCalley, 2015). They are comprised of "smart machines, warehousing systems and factories that have been developed digitally and feature integrated end-to-end Information Communication Technology (ICT)… …This not only allows

production to be configured more flexibly but also taps into the opportunities offered by much more differentiated management and control processes" (Kagermann, 2013). This vision of an inter-connected factory that utilises IoT in the I4.0 future, is best illustrated by Schweichhart (2016).

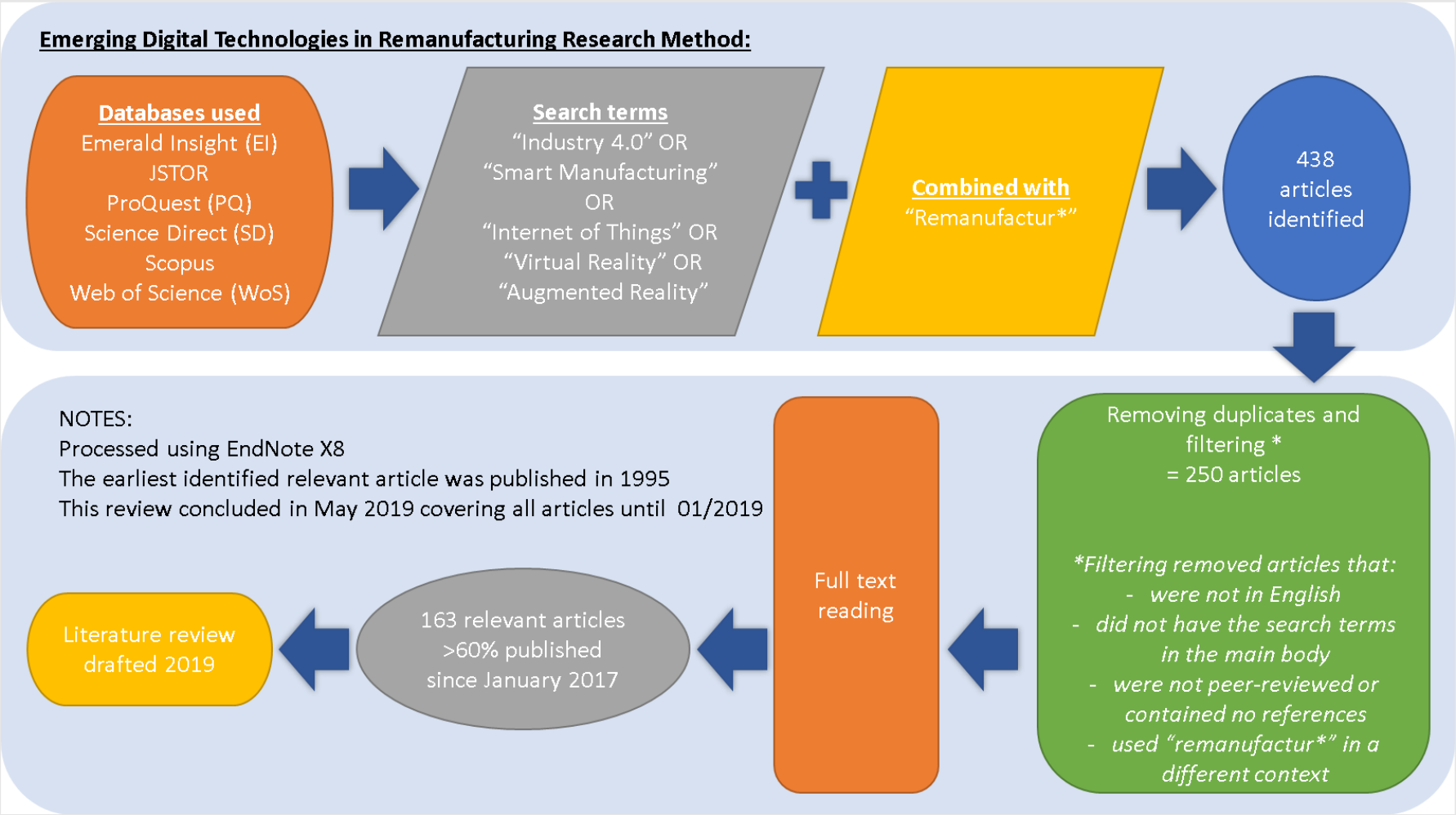
The IoT is a "global infrastructure for the information society, enabling advanced services by interconnecting (physical and virtual) things based on existing and evolving interoperable information and communication technologies" (International Telecommunication Union, 2012). This networking of products through the IoT makes it possible to connect the entire manufacturing process converting factories with differentiated values streams, into smart environments (Stock and Seliger, 2016).

VR utilises computer graphics to enable users to view 3D products or environments, with AR an extension to this, overlaying computer-generated information onto real-world objects (Grier *et al.*, 2012). The remanufacturing sector is heavily reliant on manual processes (Butzer and Schötz, 2016). The application of I4.0 and the IoT supported by VR and AR systems will be explored in this review to better understand how it may increase automation and thus the capability of this sector.

3.3 Method

As the I4.0 revolution is represented by the connectivity of machines, artificial intelligence (AI), big data and robots on the IoT (Park, 2017) and emerging digital technologies include I4.0 (or Smart Manufacturing), IoT, VR and AR (Chang, Ong and Nee, 2017a), this collection of terms were used to search six databases to explore how they relate to remanufacturing (Figure 3-1). This systematic approach is used to allow for the process to be reproduced, a key quality when completing a review of this type (Seuring and Gold (2012)).

Figure 3-1 Research Method



Full-text reading revealed that the emerging technologies were intertwined to different extents within (re)manufacturing and there were gaps in the research. Overlaps in the material also existed. In order to provide uniform coverage without biases, the articles were categorised by 'value creation factors'. Those factors were utilised as it was the "interconnection of value creation networks in industry 4.0 [that] offers new opportunities for the realization of product life-cycles in closed circuit and industrial symbiosis" (Carvalho *et al.*, 2018). Trends and opportunities to digitalise from supplier to customer using a 'value creation module' were presented by Stock and Seliger (2016) in their vision of integrated Industry 4.0 technologies in smart factories (Figure 3-2).

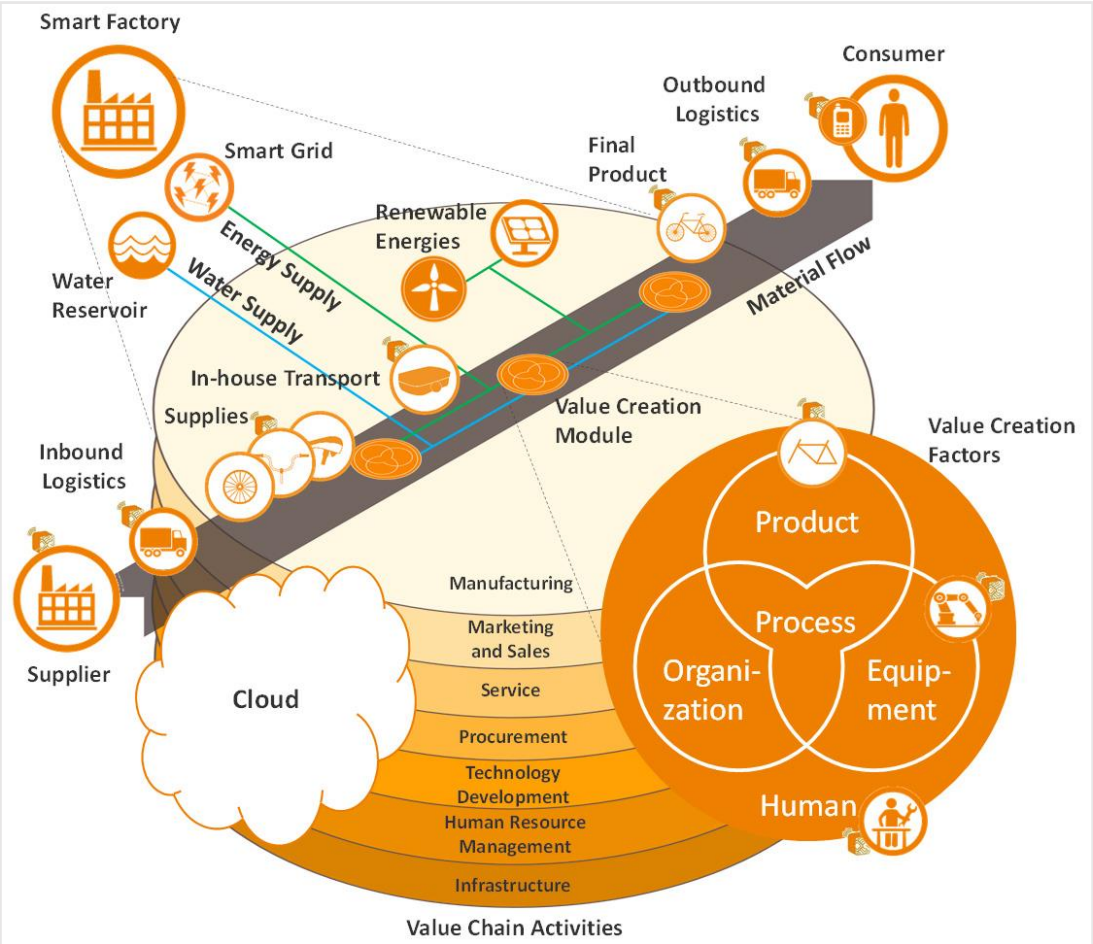


Figure 3-2 The factors that form the Value Creation Module (Stock and Seliger, 2016)

The value creation module was built on four factors: product, equipment, process and organisation (Stock and Seliger, 2016). These factors were used to categorise the articles discussed in this review to drive value creation in remanufacturing as follows: product (section 3.4), equipment (section 3.5), process (section 3.6) and organisation (section 3.7), with section 3.8 summarising research trends and gaps, drawing conclusions and recommendations for further work.

3.4 Product-Related Work

This literature review identified two main streams of research emerging at product level for remanufacturing. 'Additive manufacturing (AM) for repair and replacement' and 'data carrying devices to support EoL processing'. Interestingly both streams are already found in manufacturing supporting the belief that the "capacity of industry 4.0 to really bring [sustainable practices including remanufacturing] to fruition… is largely due to the high level of virtualization, digitization and integration expressed by the technologies that exist today" (Carvalho *et al.*, 2018).

3.4.1 Additive Manufacturing (AM) for Product Repair and Remanufacture

Rejeski, Zhao and Huang (2018) explored AM with respect to the environment, recommending research into remanufacturing issues and opportunities of hybrid material and structures, customised products, and how intellectual property (IP) is managed. They suggested that thought must be given to a product at EoL for the wide-scale adoption of AM processes to be successful, a subject considered by Müller *et al.* (2018) who presented a demonstration tool for designers of AM products, to capture and display different lifecycle implications at the design stage. The flexibility of AM, along with its reliance on designs to be available digitally, means that it could also be used once a product is Middle-of-Life (MoL) to support rapid design

modification should an unexpected failure or behaviour occur (Müller *et al.*, 2018), or for repair/remanufacturing activities providing aftersales services for companies employing product-service business models (Murmura and Bravi, 2018).

AM has the potential to contribute to sustainability through being combined with IoT technology but the full consequences of realising this are difficult to predict (Rejeski, Zhao and Huang, 2018). This is supported by Despeisse *et al.* (2017) who reviewed 3D printing with respect to the circular economy (CE), suggesting 3D printing had the potential to support sustainable manufacturing but questioned the current trajectory of adoption and whether the flexibility of the AM components complicated, rather than simplified, EoL processing. Reflecting on the integration of 3D printing with IoT and I4.0, they recognised the industrial landscape was already changing and concluded with a research agenda to evaluate issues and opportunities to achieving a CE. Yeo, Pepin and Yang (2017), on the other hand, identified a set of product characteristics (high-value, durable, with long technology cycles and the potential to be leased) where AM could be effectively implemented. They focused primarily on AM for component repair and the parallel introduction of the emerging digital technologies whilst offering a clear vision of a future factory for products with these characteristics, reviewing advanced manufacturing methods for remanufacturing.

3.4.2 Data Carrying Devices in Products to Support Remanufacturing

There were several data carrying devices (DCD) integrated with emerging digital technology discussed in the literature, the most popular being Radio Frequency Identification Tags (RFID). A thorough review of RFID in remanufacturing was presented by Ferrer, Heath and Dew (2011). Issues with RFID are explored by Nowakowski (2018) using a case study to test capabilities and costs highlighting the effects of transmitter-responder distances, line-of-sight, and component material on signal strength, and 2D-code damage on readability and errors.

Gao, Xing and Marwala (2013) employed an algorithm to optimise the arrangements of RFID systems to improve reliability to support remanufacturability assessments, but information on how this could be applied in industry was vague.

Other DCD included Quick Response codes (QR), 2D-codes (QR or Data Matrix) and Passive Self-Sensing Tags (PSST). Regardless of the DCD used, the systems generally target the same requirements, namely, the need to provide product data for real-time:

- monitoring and allocation of remanufacturing resources
- MoL decision-making for End-of-Life (EoL) processing (remanufacture / dispose etc.)

3.4.3 DCD for Monitoring and Allocation of Resources

The use of DCD in remanufacturing is varied, with examples including the tracking of operators, resources, equipment and products through the value chain. Whilst the concept presented by Zhang *et al.* (2015) to utilise RFID and real-time data for dynamic optimisation of shop-floor material handling was for manufacturing, it is also applicable in remanufacturing. RFID was integrated with IoT and I4.0 for the tracking of reverse logistics vehicles (Liu, Zhang and Wang, 2018) and pallets (Tornese *et al.*, 2018) for real-time data-driven optimisation of resource and task allocation. RFID and the IoT were also used by Zhang *et al.* (2018a) to provide information on resource availability to support real-time production scheduling for an engine remanufacturer, similar to the works of Huang *et al.* (2017) who explored the using of RFID to build a dynamic holographic workshop map. While Gu *et al.* (2017) fitted RFID to Waste Electronic and Electrical Equipment (WEEE) to manage the product through repair or EoL processing, de Sousa Jabbour *et al.* (2018) suggested they could be used in the management of services such as water and power, whereas Yi and Park (2015) described the installation of a process controlled, IoT linked, multi-stage disassembly line for End-of Life Vehicles (ELV),

with data collection that was remotely accessible. Using RFID tags on slave trolleys containing load cells, they linked the ELV to workstation instructions to drive process conformity and accurately monitor and report material weights.

3.4.4 DCD for MoL Decision-Making for End-of-Life (EoL) Processing

It was necessary to explore the use of the DCD to support MoL activities as the information gathered during this life phase may well assist EoL processing. A stand out example included Ness *et al.* (2015) who used RFID integrated with a stress sensor fitted to structural steel to assist in the reuse/remanufacture of EoL structural steel for new applications using Building Information Modelling and VR models. Presenting a theoretical case study, they evaluated potential environmental and business benefits and offered an insight into the range of applications of RFID for product level remanufacturing. A more detailed appraisal of the economic benefits of the use of DCDs and sensors embedded in wind turbine systems is documented by Dulman and Gupta (2018). Additionally, Stock and Seliger (2016) successfully demonstrated the retrofitting of an accelerometer and PLC to a MoL milling machine to form a CPS capable of interacting with others via IoT, providing a vision of intelligence upgrading for high-value, long-life products, but overall little consideration has been given to the connection of products already containing embedded or external networking capability. These need to be considered as I4.0 relies on the interconnection of all networked products.

Air purifiers using passive RFID tags for internal data transfer integrated with sensors, read by mobile data systems, linked together in a web-based environment to share information to better support MoL and EoL activities, were the subjects of an extensive paper by Li *et al.* (2015). Musa *et al.* (2014) successfully demonstrated the integration of RFID, sensors and GPS into a single chip for MoL data transfer after a review of mobile Internet, GPRS, 4G, and RFID. “It can be said that the main benefits of these technologies are that they enable enterprises to be

more coordinated or integrated, smarter, leaner, more agile, efficient and productive" (Musa *et al.*, 2014). However, they suggested a level of intelligence and decision-making was required to provide meaningful MoL information for remanufacturing, a subject that is rarely discussed but relevant, and adds further complexity to data management, reliance and product whole-life support. Additionally, the willingness of customers to participate in the collection of data along with the role that they play in data generation, collection and sharing is a concern (Field *et al.*, 2018).

Wang *et al.* (2014) presented an interesting and applicable novel architecture where a WEEE product labelled with a QR code filled with BoL/MoL data provides information to a cloud service. The system was aimed at engaging the consumer when a product is no longer required or fails. The user scans the QR code on the product triggering the upload of data, employing a web-based interface where a cloud service coordinator can cross-reference the demand and arrange the relevant EoL service (incl. remanufacturing).

Yawei *et al.* (2017) provided a detailed review of Passive Self-Sensing Tags (PSST) that could be used to give information about the material it is placed on through the changes associated with the emitting parameter. "It can be envisioned that PSST holds potential to replace some conventional wireless sensors as a new sensor node in the IoT era. More importantly, the static and dynamic information collected by PSSTs during a products life-cycle could improve logistics management, health monitoring, maintenance, remanufacturing and process development." (Yawei *et al.*, 2017).

3.5 Equipment-Related Work

This section discusses emerging digital equipment, tooling and systems (not fitted to the product) found in the remanufacturing space. Synthesis has been based on Ranky (2001) who

discussed the trends in disassembly (a major process steps in remanufacturing) highlighting two research streams:

1) the development of technology, methods and algorithms for web-based virtual disassembly platforms

2) smart robotic disassembly cells using intelligent sensing and real-time adaptation

These streams were adapted to summarise the findings related to "equipment", but as remanufacturing consists of more than disassembly (All-Party Parliamentary Sustainable Resource Group, 2014) "disassembly" was replaced by "remanufacturing" in the section titles.

3.5.1 Technology for Web-Based Virtual Remanufacturing Platforms

The management and activity of disassembly is not unique to remanufacturing. It also supports MoL maintenance, MRO, servicing and upgrade activities along with EoL processing. It is therefore beneficial to consider disassembly planning (DP) at the product design stage. DP for remanufacturing is a popular area for VR application research, as "virtual reality implies a quality revolution in the manufacturing system and in product performance and quality" (Coates, 2000) that is most effective at the product design stage (Chang, Ong and Nee, 2017a). The accuracy of the decisions made at the BoL for EoL processing may benefit from IoT through the feedback of information from MoL activities including usage, servicing and recovery (Brundage *et al.*, 2018).

Automated disassembly sequence planning (DSP) combined with VR is the subject of several papers including that by Siddique and Rosen (1997) who uses a vehicle console as a case study allowing designers to critique disassemblability of different models. Similarly, Zwolinski, Tichkiewitch and Sghaier (2007) describe the use of VR at the design stage with design-for-(dis)assembly rules to meet changing requirements. Chung and Peng (2008) describe a web-

based VR environment for dynamic selective DSP using real-time resource data to calculate process parameters, whilst Mircheski and Rizov (2018) demonstrated a non-destructive planner supported by AR and RFID.

Santochi, Dini and Failli (2002) provided a detailed critique of computer-aided disassembly software to assist DP. Modularising the software's features, capabilities, speciality or overlap, they identified a lack of development in the areas of design for DP, subassembly detection, and systems capable of dealing with destructive disassembly. More recently, Ghandi and Masehian (2015) called for additional research focused on the (dis)assembly of flexible components, tooling and fixtures, thermal expansion, contraction and deformation in their thorough review of (dis)assembly path planning methods including VR.

More generally, Mourtzis, Doukas and Bernidaki (2014) explored developments, applications, trends and challenges in simulation methods including VR and AR in product/process design, planning and verification. Whilst their work focused primarily on manufacturing, it does pertain to remanufacturing, particularly when it has the same goals as manufacturing in terms of flexibility, quality, velocity and cost (Ferrer, Heath and Dew, 2011) and current methods *can and should* be used in remanufacturing (Ferrer and Clay Whybark, 2000). The illustration by Mourtzis, Doukas and Bernidaki (2014), adapted to include training, captures the manufacturing, and potentially the remanufacturing, business function where simulation methods and tools such as VR, AR and digital twins could be utilised (Figure 3-3).

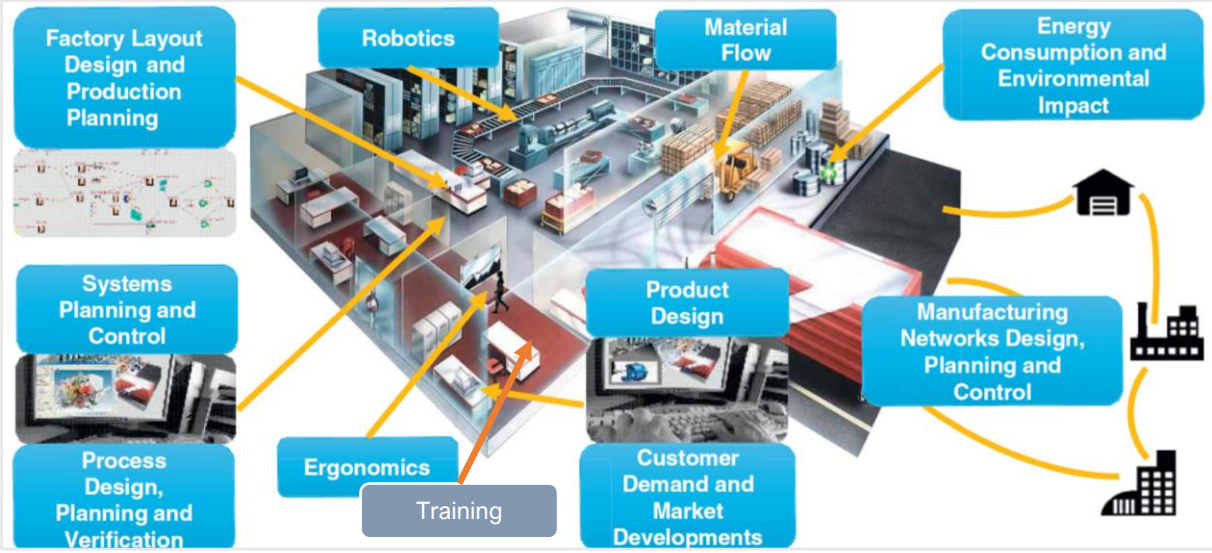


Figure 3-3 Remanufacturing simulation (adapted Mourtzis, Doukas and Bernidaki (2014))

Takata, Isobe and Fujii (2001) used a 3D product model to provide DSP, direction and tooling information to the operator on a head-up display. The model was updated in real-time considering feedback from 6-axis sensors fitted to the operator's gloves. They identified the need to expand the algorithm for operation monitoring to recognise more generic movements, a limitation potentially alleviated by tracking the product (not the operator), as proposed in Chang, Ong and Nee (2017) and Osti *et al.* (2017).

Chang, Ong and Nee (2017) used AR to communicate an auto-generated DS to the operator, overlaying the real environment with text and images, demonstrating the application on the disassembly of a coffeemaker (Figure 3-4). Similarly, Osti *et al.* (2017) demonstrated an AR system that used CAD, AR, a Leap Motion Controller device, glasses and a strategy evaluation algorithm, that permitted the visualisation of information concerning the disassembly path and tooling required to complete the task. On the other hand, Mircheski and Rizov (2017) utilised a mobile phone or tablet to present the DS information. From a technical perspective, all four papers presented simple but capable demonstrations of CPS offering a vision of future AR-supported disassembly activities.

Figure 3-4 AR demonstrated in disassembly (Chang, Ong and Nee, 2017)

Menn *et al.* (2017) explored the use of 3D-PDF, Utility-Film (a language independent video tutorial that represents the real-world) along with illustrated manuals to train remanufacturing operators. Evaluated with respect to product assembly time, instruction creation time, ease of distribution, usability, assembly error susceptibility and changeability, interactive 3D-PDF was identified as the best solution. Following on from this, Menn *et al.* (2018) discussed a layered curriculum for special machine-tool build and repair training (potentially representative of high-value, low frequency product remanufacturing). Using AR the operator could engage with a mock AM product to establish base knowledge before progressing onto the real product using interactive 3D-PDF to assist with variety familiarity. Finally, Menn, Ulbrich and Seliger (2018a) documented the results of a questionnaire aimed at capturing feedback from machinery Field Service Engineers after they had used interactive 3D-PDF Learnstruments (physical interactive objects that assist with knowledge transfer of functional tasks in the workplace (McFarland *et al.*, 2013)). They suggested that this method could support training. However, issues with limited portability, susceptibility to errors, and high cost of the equipment were identified as barriers to implementation.

Müller *et al.* (2016a) documented the use of a simulated teaching game to support the up-skilling of operators using VR and motion tracking technology to encourage learning in manual

work environments, relevant to remanufacturing due to the high proportion of manual processing. Similarly, Müller *et al.* (2016b) presented an AR tool designed to transfer knowledge to trainee operators through the tracking of their hand movements monitoring them against a pre-defined plan using a Kinect camera. Interestingly, the results suggested paper-based training provided faster learning and fewer operational errors, but problems with the hand recognition methods and differences between the teaching/learning environments were recognised as potential error sources. However, the concept does show some promise for remanufacturing, as does the idea of using VR integrated with a portable coordinate measurement machine to drive standard measurement control for inspection activities (Segovia *et al.*, 2015). So far, there has been no clear direction or demonstration of how this could be achieved.

In a learning factory environment, Uhlemann *et al.* (2017a) compared a process digital twin (not realised, only described) with value stream mapping, evaluating the characteristics of both methods, as low, medium or high without clear criteria. This implied an over-simplification of the pre-requisites for building a digital twin and potentially over-rated the benefits. However, as VR has already been used in process planning, it may be possible to overlay real-time information to generate a process digital twin that could be used for educational or management purposes.

3.5.2 Methods (Systems) for Web-Based Virtual Remanufacturing Platforms

The methods identified in this review related to the layering of different technologies to support the sharing of product and process information. Research in this field was limited and disconnected but did provide a range of concepts across different remanufacturing sectors.

Automated identification and assessment of inbound core was the focus of Schlüter *et al.* (2018) who proposed a CPS inspection "Logic.Cube" containing cameras and scales, whereas Muftooh *et al.* (2018) demonstrated the feasibility of videogrammetry to generate a low-cost 3D model of an engine to determine influential parameters that may affect the remanufacturing process. Also in inspection, Stark *et al.* (2014) explored a multi-layered solution to improve success rates and increase automation in printed circuit board (PCB) MRO, overlaying CT and 3D scanning outputs to build error-free netlists for reverse engineering activities, using flying probes for continuity testing, and algorithms for component identification.

Should a robotic remanufacturing process exist, a cloud service could be used to provide 'Robot Control-as-a-Service' to realise real-time adaptive control to deal with uncertainties in EoL product states and unforeseen events (Adamson *et al.*, 2016). Similarly, adding I4.0 technology to machine tools could support the development of web-based distributed process planning in decentralised dynamic (re)manufacturing environments (Wang, 2013).

In sectors that have legislated targets e.g. ELV, where closer monitoring and reporting is required, it may be beneficial to install an IoT linked remanufacturing monitoring system with remote data accessing "designed and implemented to check whether the dismantled parts are properly recycled, and to collect recycling data… …[as] the real recycling rates are expected to be much lower than the depicted values since they are mostly based on recyclers' reports" (Yi and Park, 2015).

Wang, Ong and Nee (2018) explored ubiquitous technologies in research including IoT, big data, RFID and cloud systems with a section specifically dedicated to remanufacturing. They suggested new opportunities existed for the remanufacturing industry through the harnessing of a product's lifecycle data to make decisions on its future.

Once data has been captured and analysed successfully, the use of digital twins for product/process optimisation (in remanufacturing or in MoL scenarios) has been proposed but has been limited in demonstration or application. Uhlemann, Lehmann and Steinhilper (2017) proposed the use of sensor-based tracking and vision systems fitted to machine tools. The sensors and vision systems capture real-time data on product manufacturing, to provide inputs to a 'process digital twin', potentially applicable to highly automated remanufacturing facilities. Abramovici, Göbel and Savarino (2017) described the use of a 'product digital twin' allowing MoL reconfiguration options to be presented to the user via IoT and then realised, based on the results of virtual evaluation and personal preferences. Wang and Wang (2018) demonstrated a digital twin-based system for the recovery/remanufacturing of WEEE, whereas Lejon and Jeppsson (2015) demonstrated the extension of a Product Lifecycle Management (PLM) system, to support product instances and provide links to a dashboard using a low-powered wireless sensor network. A combined solution for information management of both product use and development for functional products, can be achieved by integrating MoL information with the virtual representation (Lejon and Jeppsson, 2015).

With previously untapped MoL data available upstream to suppliers and designers, information that enables decision-making activities in closed-loop supply chains can also be traceable (Li *et al.*, 2015). Tao *et al.* (2016) used mobile phones as a case study to discuss the opportunities and challenges of IoT (using RFID) for lifecycle energy management, how and where the data could be used in design, production and MoL suggesting it improved EoL decision-making. Through correct management of BoL, MoL, and upgrade options data, the alignment of the real product and its digital twin allows for the management and evaluation of information and environment extending product life, turning potential EoL products back to in-life products through remanufacturing.

In order to realise these opportunities, there is a need for standardised machine readable information to link software packages to support through-life data management for "fast and error-free processing of engineering information" *(Ivezic, Kulvatunyou and Srinivasan, 2014)*. This subject was reviewed by Pagoropoulos, Pigosso and McAloone (2017) who detailed the use of digital technologies in the CE suggesting greater focus was required on data architecture and integration. Schmidt, Wang and Galar (2017) discussed different data types and their availability within a manufacturing ICT system suggesting ontologies overlap which allowed for data use and knowledge share across platforms. However, they identified that links needed to be explicitly defined and whilst "data from the whole population of identical or similar components could be retrieved… …data from a population of components cannot be simply aggregate, without consideration of contextual information" (Schmidt, Wang and Galar, 2017). This adds significant complexity to the real-time monitoring of MoL products or data collection for EoL processing. Vast quantities and variability in the quality of the data will need to be handled but traditional methods are not able to deal with the demands of big data (Tsai *et al.*, 2015). Remanufacturing could benefit from big data and its use has been proposed in several areas including:

- The optimisation of production performance of AM (Majeed, Lv and Peng, 2018).
- The collecting of data relating to a device from BoL to EoL, monitoring the generation and trade of WEEE for the purposes of law enforcement, policy making and administration (Gu *et al.*, 2017).
- The coordination and analysis of materials information, with potential to provide EoL product knowledge (Jose and Ramakrishna, 2018).
- The tracking of changes made to products using big data methods during MoL MRO to support operations management (Roy *et al.*, 2016).

- To drive decisions in the supply chain (Nguyen *et al.*, 2017, Viet, Behdani and Bloemhof, 2018), cleaner production to improve competitive advantages (Zhang *et al.*, 2017a), or PLM (Zhang *et al.*, 2017).
- Dynamically mapping relationships between disassembly attributes and industrial robot's (IR's) real-time data using a meta-data model of IR, the data source and classification of the disassembly process, and the in-cycle data which is mined and analysed using the Bees Algorithm (Zheng *et al.*, 2017).

The diversity of the applications for big data in remanufacturing can be seen above but gaps exist, and an end-to-end view is yet to be presented. Friedemann *et al.* (2016) identified two key publications related to standardisation in I4.0 including 'Reference Architecture Model Industrie 4.0' and the 'Industrial Internet Reference Architecture'. However, solutions need to be found in the compatibility of definitions for remanufacturing along the entire value chain, information security and confidentiality, safe sharing of sensitive data between stakeholders, and the establishment of stable interfaces for transactions and communications to occur (Jensen and Remmen, 2017). Other concerns include security, accuracy of sensors, standardisation of devices and the energy use associated with IoT technology, efficient naming and identity management, scalability, and the need for more "high-powered information collection, advanced data processing algorithms, and information gathering platforms" *(Tao et al., 2016).*

3.5.3 Algorithms for Web-Based Virtual Remanufacturing Platforms

Algorithms have been incorporated into some of the systems already discussed to assist in the identification of components (Stark *et al.*, 2014) and motions (Takata, Isobe and Fujii, 2001), or for DSP (Osti *et al.*, 2017). More specifically to remanufacturing, Hao *et al.* (2018) discussed a hybrid process planning algorithm to determine a reasonable machining route for both CNC machining and AM for product remanufacturing using CAD. Additionally, Zhou *et al.* (2018)

presented a solution to generate a service Bill of Materials (sBoM), that could also be applied to remanufacturing as an EoL BoM. The sBoM would be created from a general product structure BoM via a conversion tool (processing data potentially from IoT sources) demonstrating significant improvements in sBoM accuracy, and a reduction in lead-time and labour requirements. In a different application aimed at identifying the most suitable EoL products for remanufacture, Meng *et al.* (2016) described a decision-making tool that used a hybrid of calculations including cost-benefit analysis and a fuzzy inference model (EoL product quality based on use, performance and reliability), that estimated recovery value and cost. Combined with qualitative factors including technology compatibility, market performance, environmental impact and consumer opinion, the results were ranked and were found to be superior to those obtained using other methods.

Interestingly, however, Craig (2017) highlighted the risks posed to the increasing reliance on complex algorithms working with digital technologies, warning the greater the complexity, the less transparent the algorithm became, making systems vulnerable to (un)intentional biases with potentially catastrophic business consequences. As an alternative to using algorithms to interrogate raw data, Zhang *et al.* (2018) presented a solution that took images of waveforms and evaluated the pixels, just as humans would look for trends in graphs, for automatic identification and classification of machine conditions.

3.5.4 Smart Robotic Remanufacturing using Sensing and Real-Time Adaptation

The only paper that successfully demonstrated a robotic remanufacturing solution referencing IoT, I4.0, AR or VR was that by Ruggeri *et al.* (2017). Mentioning I4.0 briefly as a key research trend in human-robot collaboration, they presented a reconfigurable semi-collaborative cell using the ABB YuMi robot for PCB remanufacturing. They raised interesting issues specific to micro component handling that affected gripper design, precision of robot

movement and vision system resolution. The latter two issues were also recognised by Stark *et al.* (2014) as they discussed similar micro-scale environments. The 'training' of a robot using a vision system to track human movements and tooling to repeat the disassembly of a TV was discussed by Vongbunyong, Vongseela and Sreerattana-aporn (2017) but was not realised, possibly due to the large positioning errors inherent in the proposed system.

Whilst there appeared to be a lack of smart robotic remanufacturing demonstrations, there is still an expectation that they will be utilised in the remanufacturing factories of the future (Agency for Science, 2016) suggesting more research is needed to realise it. Additionally, as full automation of the EoL disassembly process is unlikely due to variations in core quality and quantity etc., partial automation using collaborative robots, or robots in a collaborative way, may offer a solution (Chen, Wegener and Dietrich, 2014, Wegener *et al.*, 2014, Wegener *et al.*, 2015). Faber, Bützler and Schlick (2015) discussed collaborative working from an ergonomics perspective suggesting older operators could be supported by robots, a belief shared by the Society of Motor Manufacturers and Traders (SMMT, 2017), and Li, Barwood and Rahimifard (2018) who provided an extensive review of robots and automation in disassembly.

Bogue (2017) reviewed current standards and their fit to the emerging collaborative robot offering, focusing on ISO/TS15066:2016 (International Organization for Standardization, 2016) before providing an interesting insight into their use outside of the guarded factory environment (more reflective of a collaborative remanufacturing factory), and the different solutions manufacturers have used to meet the standards. Marvel and Norcross (2017) critically analysed ISO/TS15066:2016, specifically the scenarios where the minimum protective distances between robot and operator in the collaborative workspace, below which a safety-rated, controlled stop is triggered highlighting the instances where the assumptions may not be sufficient to protect the operator, or where a stop would be triggered by a scenario that is not

dangerous. Han *et al.* (2018) looked to improve response times of collision detection and real-time path re-planning for robot arms using a human arm (modelled as cylinders) as dynamic obstacles. Meziane, Otis and Ezzaidi (2017) described the creation and linking of a grid, waypoints and smoothing polynomials for the trajectory planning of robot motion in order to avoid moving objects and jolting of the arm.

3.6 Process-Related Work

This section considers the remanufacturing business process with respect to its key interfaces (customers and suppliers). The evolution of I4.0 technology has opened up several parallel process improvement opportunities, including real-time monitoring and allocation of resources, EoL and MoL decision-making. Potential applications expand beyond remanufacturing to MoL MRO strategies. The link between remanufacturing and MRO should not be ignored with many articles discussing the benefits of monitoring products at the MoL stage. This relationship will be further explored along with real-time monitoring and the potential to improve core visibility.

3.6.1 Remanufacturing for Maintenance

Predictive maintenance is one of the leading use cases for IoT and I4.0 (Madslien, 2018) and with the process of maintenance acting as both supplier, through the provision of cores, and customer, as a user of remanufactured products, there is a need to reflect on the interconnected relationships between them in this new digital age.

The purpose of a product from a lifecycle management perspective is to meet user requirements, minimise environmental impact and in some instances maximise profit, each influenced by customer demand and product condition, deterioration or failure (Takata *et al.*, 2004). It is necessary to recognise the "optimisation of a product‘s life cycle is a strategic objective of development for industrial manufacturing" (Westkämper, 2003). Gao and Wang (2017)

discussed sustainable research practices in machine tool MRO, suggesting repair and retrofitting is more common than remanufacturing in this high value sector. Remanufacturing is only likely when the product no longer meets the expectations of its user, or when there is no better alternative or cost-effective product available.

Franciosi, Lambiase and Miranda (2017) discussed the development of a model to support decision-making through the evaluation of different maintenance options for the replacement of failed parts with either new, reconditioned, remanufactured or used spares to promote more sustainable practice. The authors identified I4.0 technology as a tool that could improve the availability of component data. They considered using a decision-making tool only after a component had failed. However, their tool has the potential to support MoL opportunities associated with improved maintenance. These aspects were thoroughly explored by Roy *et al.* (2016), considering the assessment of product health and degradation information through IoT and I4.0 to support continuous maintenance for product improvement and life extension. Similar reviews of techniques designed to assist in extending life, analytical methods for estimating recoverability and remaining machine life (Gao *et al.*, 2018) and the implementation of prognosis and health monitoring of machines in the smart factory (Gil-Yong *et al.*, 2018), appear to align with the opinions of Ondemir and Gupta (2014). The latter authors have suggested that correct application of this monitoring and prognosis offers a solution to a significant remanufacturing planning problem, the management of uncertainties in the condition of EoL products, and the impacts of these on recovery operations and profit.

Also considering high value assets like machine tools, Westkämper (2003) discussed assembly and disassembly from a lifecycle perspective and the networking of assets for service provisioning, calling for the consideration of parallel progression. He highlighted that during the lifetime of a manufacturing centre, technologies, capabilities and efficiencies of new

products will evolve and it is the difference between the two entities that affect consumption and life-expectancy. Similarly, Xiao *et al.* (2018) explored the LCA of heavy-duty off-road (HDOR) vehicles remanufactured in different locations and compared them against that for a newly manufactured product to evaluate the resulting revenue and environmental impact. Considering production volumes and life distribution expectations, they estimated the peak in the EoL of a specific product to support remanufacturing process planning.

3.6.2 Remanufacturing and Real-Time Monitoring

Ondemir and Gupta (2014) provided a detailed insight into 'remaining useful life' as an indicator of product quality to feed into decision-making tools that optimised disassembly costs and process planning. Describing an interesting integrated system using RFID and embedded sensors to provide BoL and MoL data to EoL processing systems, they identified the serial numbers of the products to be remanufactured, and the recovery options available based on the perceived product quality.

Adding I4.0 technology to products for MoL monitoring and real-time management has been demonstrated with the possibility to develop holistic self-management systems Ivezic, Kulvatunyou and Srinivasan (2014). Whilst it could become economically viable for complex high-value products (like HDOR parts that are important, competitive and very dynamic in European remanufacturing (Saidani *et al.*, 2017)) to contain smart DCD, it makes little economic sense to add them to low-value products as the variety, volume and velocity of data, its security, the efficiency of processing, along with conflicting requirements of stakeholders, add complexity and cost to its implementation (Gu *et al.*, 2017). Instead, there is a need to develop processes and systems for efficient and effective disassembly and recycling, or hybrid technical concepts that integrate e-services (Westkämper, 2003) for low value and medium value products, respectively.

3.6.3 Remanufacturing Core Supply

For remanufacturing to be economically feasible, there must first be availability of core and a demand for remanufactured products, with the acquisition of EoL products being the first step in the remanufacturing system (Jiaping *et al.*, 2015).

As IoT has the potential to digitally link the supplier and customer (Man and Strandhagen, 2017), it may assist in the procurement of used products (Abubaker *et al.*, 2017) supporting remanufacturing core acquisition. Vikas *et al.* (2016) summarised the diversity in reverse supply chains, highlighting the need to better understand characteristics to optimise customer satisfaction and to best utilise resources. They stated that the "management of returned items is now perceived as an opportunity to improve customer service perceptions and loyalty" (Vikas *et al.*, 2016).

Ruggeri *et al.* (2017) considered the remanufacturing potential of PCBs, and mobile phones were used as examples in five articles suggesting there is a vision to consider the remanufacturing of consumer electronics. With more than 1.5M smart phones sold in 2017 (Statista, 2018) there is growing recognition that low-value, high-volume core can be valuable when reclaimed en masse. To exploit this opportunity, Apple Inc. presented "Daisy" in 2018, an automated cell capable of dismantling two-hundred iPhones/hour (Apple Inc., 2018). Currently designed to dismantle iPhones for recycling, the same facility could potentially be used to disassemble them for core reclamation and remanufacturing. Disassembly is a key activity in remanufacturing that is more challenging to automate than assembly due to variability in the physical condition of EoL products (Vongbunyong et al., 2017).

Visibility of potential core is key to business planning and as already identified it can be facilitated by DCD and real-time monitoring. The increase in connectivity achievable with IoT

devices, combined with the development of core finding web-based systems could transform the remanufacturing industry. Ryen *et al.* (2017) discussed the application of a nature inspired foraging model for WEEE core sourcing using an 'E-waste forager', translating ecological model parameters and animal behaviours into e-waste equivalents. They proposed the imitation of nature to "develop the partnerships, infrastructure, tools, and policies needed to ensure a long lasting, adaptable, and profitable e-waste ecosystem that can endure material scarcity, price fluctuations, or innovation changes" (Ryen *et al.*, 2017).

3.7 Organisation-Related Work

The move in manufacturing towards more sustainable methods and the parallel emergence of I4.0 necessitate changes in business strategies and management styles. Sustainability in companies can be supported through the integration of management systems, with a combination of bottom-up and top-down approaches being most effective (Lukman *et al.*, 2016).

Should a business translate towards providing services as well as products as part of a Product-Service-System (PSS), the organisational structure will need to be modified to cope with the new challenges (Stark *et al.*, 2014) and, as the remanufacturing industry can provide significant support functions to PSS organisations, they will have to adapt accordingly. This will force remanufacturing firms to invest in more sophisticated ICT to take advantage of BoL and MoL data for EoL processing, and to regulate sustainability consciousness to meet changing customer and corporate environmental expectations.

3.7.1 Business Models

According to Lazarevic and Valve (2017) in their article that discussed expectations towards the CE transition, digital enabling technologies were key to enhancing real-time information

exchange amongst users which could facilitate business models for repair and reuse. Additionally, there is general agreement that the success of a CE depends on new business models that extract the value that is still embedded in EoL product (Esmaeilian et al. 2016). The business models that best reflect CE principles provide services or solutions that are of high quality, have technology cycles that are longer than their life expectancy, and offer both short-lived and durable products with restoration methods available (Yeo et al. 2017). Interestingly the sectors that currently utilise this type of model are often influenced by local or regional regulations.

At industry sector level, there are many national and international regulations that align to the principles set out by the United Nations Sustainability Development Goals (United Nations, no date). Examples include the European Parliament and European Council's ELV directive 2000/53/EC, and Waste Electronic and Electrical Equipment (WEEE) directive 2012/19/EU, aimed at reducing waste and hazardous material to landfill (European Council, 2000, European Union, 2012). Hughes (2017) summarised the work of the EU regarding standards and legislation focusing on the effects of the 2015 CE Package that is due to develop generic standards for eco-design requirements in 2019. Covering parameters and methods to assess remanufacturability, component access to facilitate remanufacturing, evaluation indexes or criteria, identification and relevant documentation, Hughes (2017) provided an insight into impending standards before questioning how the EU could ensure that the "revolution expected to be brought about by both the 'Internet of Things' and 'Industry 4.0' deliver[s] the European Commission's goal of creating a circular economy" (Hughes, 2017).

There were also examples of industries that employ remanufacturing practices but self-regulate, that could benefit from I4.0 technology. Comparing the regulated automotive industry and the EoL directive, with the self-regulated shipping and aircraft industries, Jensen and Remmen

(2017) highlighted the high recycling rates, low material to landfill, and the different markets for reuse, as well as recognising the need for an information management system to handle data transferred through the entire product lifecycle, from all three industries. As I4.0 digitally connects the customer with the supply chain (Man and Strandhagen, 2017) it may eventually serve both regulated and self-regulated businesses. Similarly Saidani *et al.* (2017) discussed best practices and challenges comparing the HDOR vehicle industry (that is not directly legislated) with the automotive sector suggesting that embedded telematics (automotive systems that support roadside and remote diagnostics) could provide useful information for life extension and EoL decision-making.

There were various products, processes and strategies used for remanufacturing that were presented by Tolio *et al.* (2017) in their thorough review of smart enabling technologies in design, management and control using examples from well-known OEM's. Proposing a new manufacturer-centric CE model and touching on the requirements to meet it, they suggested that a higher technology readiness level needed to be achieved, particularly in the areas of integration and demonstration to support the transition to I4.0. These areas are being pursued by a number of manufacturing research collaborations as reported by Bueno, Girot and Gutiérrez-Orrantia (2017) who summarised the work across Europe, discussing existing government backed, public and private programmes, plans and roadmaps covering initiatives such as "Manufuture" and "Factories of the Future".

3.7.2 Expected Growth of ICT

Data sharing along a product's life from concept visualisation to EoL processing has already been discussed. However, to realise sustainable benefits from I4.0 including value co-creation, closer links to stakeholders, complex decision-making (through AI and machine learning), and the expansion of PSS, it is necessary to expand remanufacturing ICT capabilities. The "ICT

support sector is able to support the CE, by offering existing services in new ways, or developing entirely new services, to enable their customers to decouple profits from resource consumption" (Heyes *et al.*, 2018).

Developments in emerging technologies and CPS require exponential growth in the ICT infrastructure (Raihanian Mashhadi and Behdad, 2018), so too does the need to harness the knowledge of engineers in increasingly complex manufacturing scenarios to support the evaluation of different processing options by provisioning the relevant information to the experts at the right time (Belkadi, Bernard and Laroche, 2015). Taken from Wang (2014), Figure 3-5 illustrates the data management for WEEE through its entire lifecycle using cloud storage with a more detailed discussion and IoT application found in (Wang and Wang, 2017).

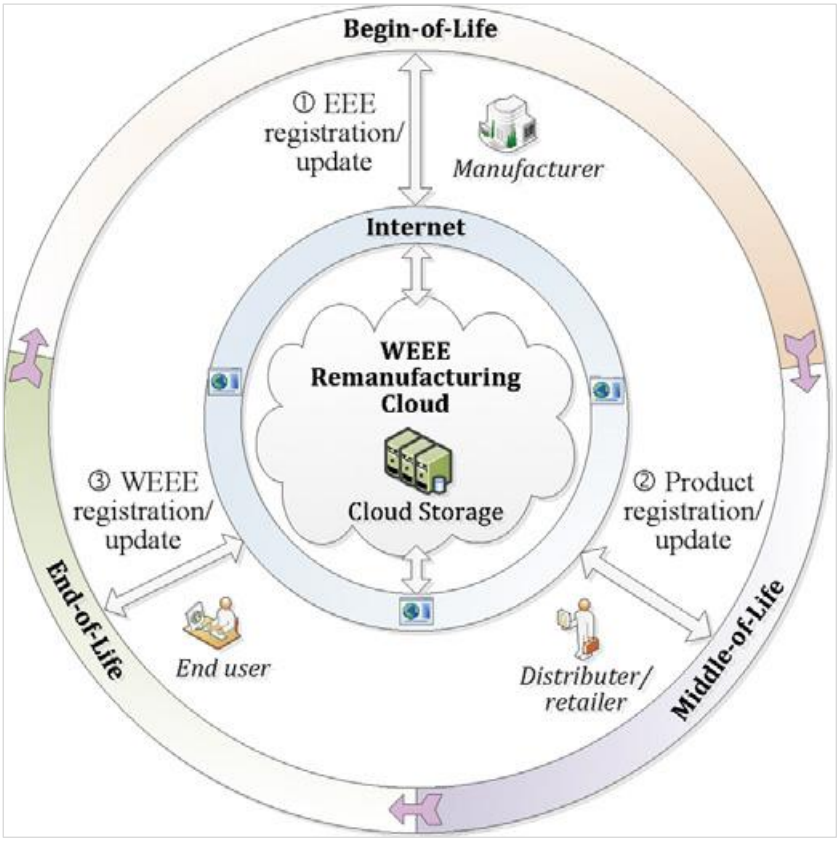


Figure 3-5 Cloud-based WEEE data management for remanufacturing (Wang et al., 2014)

This vision could also be applicable to non-WEEE products, cycling the information from OEM, to distributor, to user, and back to the OEM.

The growth requirement of the ICT provision varies depending on existing ICT infrastructure, business model, company and expectations, but opportunities exist to harness the scalability of cloud-based manufacturing systems. It can increase sustainability by supporting collaborative design, greater automation, improve resilience and enhance EoL processes (Fisher *et al.*, 2018).

Romero and Vernadat (2016) delved into the specifics of enterprise information systems (EIS), reviewing their history and future. They claimed that continued growth in cloud-based EIS could change the way businesses purchase, use and structure their ICT, allowing for highly integrated networking of industries at different levels. Jensen and Remmen (2017) suggested that integrating information in an EIS could reduce business risk through increasing product understanding. However, they also raised concerns over data management and compatibility of definitions between the stakeholders and the challenge that this posed when implementing an EIS, particularly in product stewardship business models.

Focused specifically on the standards associated with information systems for closed-loop lifecycle management using IoT, Kiritsis (2011) discussed the specifications related to data type and format, reporting on systems that offered some level of capability in this field. Aiming for seamless and transparent interoperability, they used a read-write capable RFID transmitter and receiver, linked with sensor feedback to an internet-based system, on an EoL vehicle with OEM information to make decisions on the recovery of components.

The most complete example of the ICT infrastructure required to organise data-driven products for lifecycle management (Figure 3-6) was adapted from (Zhang *et al.*, 2017) by adding 2D codes and cloud databases as these have been identified in this study as providing value to

remanufacturing. Starting at "Component 1" DCD, along with embedded and external devices, are used at BoL, MoL and EoL to support design, scheduling, optimisation, diagnostics and remanufacturing (Component 4). Components 2 and 3 represent data cleansing, reduction and post-processing before it is made available for mining to support decision-making.

3.7.3 Sustainability Consciousness

The cost of waste to the environment, the depletion of natural resources increasing commodity costs, improvements in technology and changes in consumer demands are building momentum in the support of a CE of which remanufacturing is a key strategy to increase efficient use of resources (Preston, 2012).

In September 2015, world leaders set out a declaration of commitment to 'Sustainable Development Goals' with the aim of balancing the economic, social and environmental needs of the planet by 2030 (UN General Assembly, 2015). The activity of remanufacturing links to two of the targets (9.4 and 12.5) supporting the international community's vision of increasing sustainability through cleaner technologies, processes and manufacturing strategies and reducing waste. It is no surprise, then, that sustainable development is a popular topic for researchers with enthusiasm and belief that I4.0 and remanufacturing can support it.

However, the remanufacturing business itself should also promote sustainable business practices. To lead the transition towards more sustainable businesses, Carvalho *et al.* (2018) identified two emerging types of entrepreneurs, the "ecopreneur" and the "sustainable entrepreneur". These have different objectives and approaches to building a sustainable industry, but both represent new roles and environmentally conscious leadership styles in the I4.0 manufacturing future.

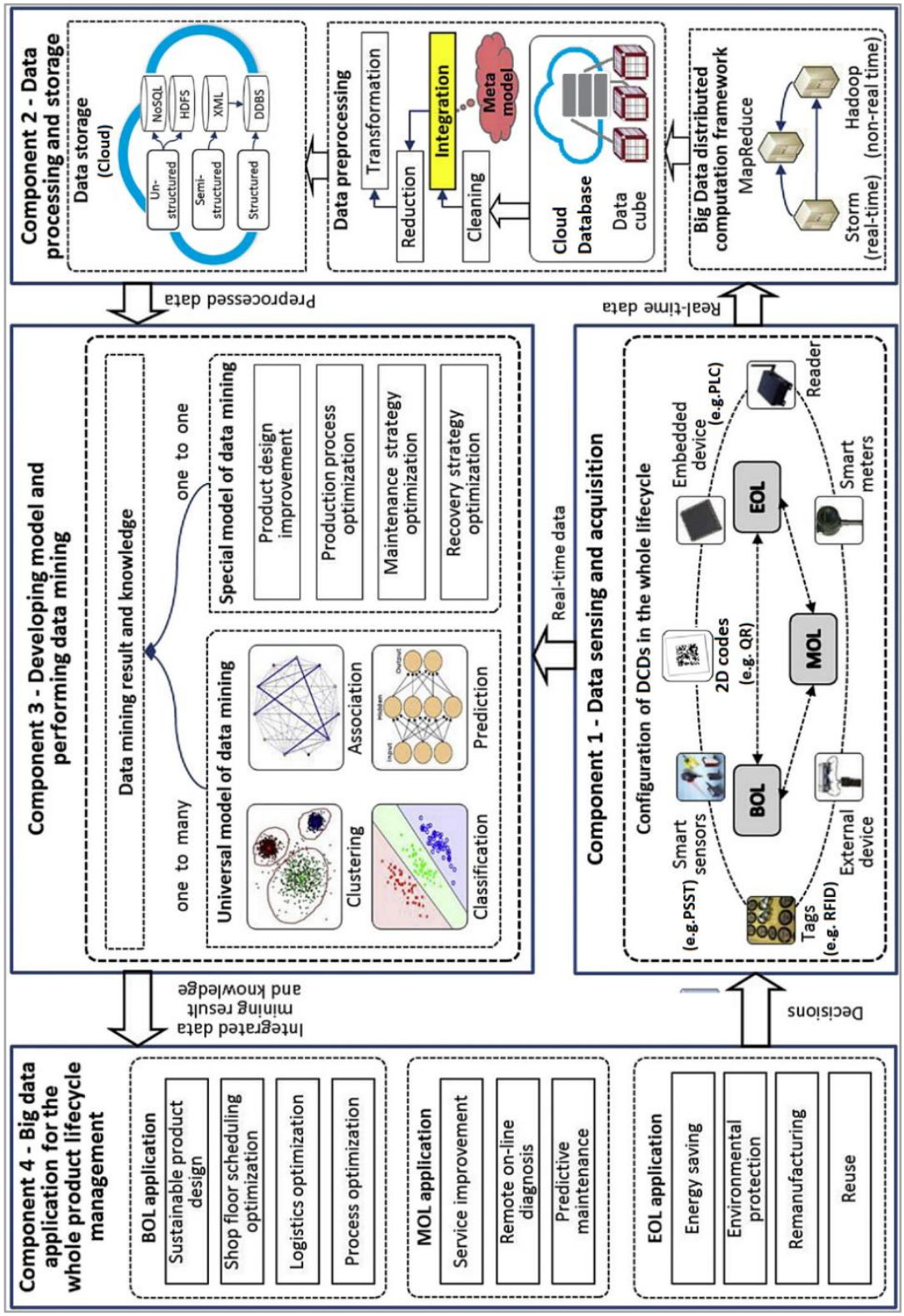


Figure 3-6 ICT infrastructure for data-driven products (adapted from Zhang et al. (2017))

3.8 Discussion, Conclusions and Further Work

This article has reviewed published work on Industry 4.0 (or smart manufacturing) technologies, in particular, the Internet of Things, Virtual Reality and Augmented Reality and their potential application in remanufacturing. It can be used by researchers in the field of remanufacturing quickly to locate relevant material and open research topics. Trends and gaps have been discussed, summarised according to four value-creation factors, Product, Equipment, Process and Organisation, and presented in Figure 3-7.

Primarily used to repair EoL products, AM systems integrated with the IoT have possibilities, but realisation has not been demonstrated and concerns exist over the current trajectory of developments in this field to support sustainable practices.

The focus of most of the papers on DCD to support remanufacturing was on the addition of 2D codes or RFID devices to carry data. Additionally, instead of relying on capturing data throughout a product's life, it may be possible to develop sensors that only send information on a change of state, i.e. when a particular measurable failure occurs. With the DCD fitted to a component in a permanent, semi-permanent or temporary application to meet the needs to track, trace or transfer limited amounts of data over short distances, it can also be retrofitted to products already in-use. For complex products finding a location for the 2D/QR code that can be line-of-sight readable can be difficult, with component properties affecting signal strength and transmitter-responder capabilities.

Product

Modifications or additions to the PRODUCT to exploit the emerging I4.0 technologies for the purposes of remanufacturing.

RESEARCH TRENDS

- The use of AM for high value product repair in remanufacturing continues to be explored
- There is a significant interest in the addition of DCD's (particularly RFID) to the product for information exchange.

RESEARCH GAPS

- There is no evidence of AM being exploited for low value mass remanufacturing.
- Little consideration has been given to the exploitation of the data carrying opportunities of already "smart" product for remanufacturing.

Equipment

EQUIPMENT proposed for the remanufacturing of the PRODUCT using the emerging I4.0 technologies.

RESEARCH TRENDS

- VR and AR to support product disassembly is a significant research area in remanufacturing.
- There is great enthusiasm for the use of big data in remanufacturing for MoL / EoL decision making and product design optimisation.

RESEARCH GAPS

- Currently there are few demonstrations of existing smart I4.0 technologies (already in use in manufacturing) being applied to remanufacturing.
- No real vision or demonstration exists on how virtual product / process twins or big data could be utilised in remanufacturing.

Process

PROCESSES to support the management of the PRODUCT and EQUIPMENT for remanufacturing using emerging I4.0 technologies.

RESEARCH TRENDS

- Researchers have linked the digitalisation of high value products and equipment with potential improvements in the processes of management of maintenance, real-time asset monitoring and remanufacturing core supply.

RESEARCH GAPS

- The remanufacturing processes for low value, mass produced products is yet to be fully explored.
- Opportunities exist in the exploration of potential links between remaining product life and core supply management or remanufacturing process strategy design.

Organisation

ORGANISATIONAL changes to support the EQUIPMENT and PROCESSES to remanufacture the PRODUCT using emerging I4.0 technologies.

RESEARCH TRENDS

- Investment in ICT is expected to support I4.0 remanufacturing and there is significant research being conducted in designing and provisioning associated architecture.
- There are many emerging business models utilising I4.0 that generally agree that I4.0 could have potentially positive impacts on sustainable remanufacturing but does not explicitly tackle sustainability.

RESEARCH GAPS

- There is an opportunity to further develop sustainable business models that utilise I4.0 specifically for the remanufacturing industry.
- No real consideration of measurements / critical success factors for tracking progression towards sustainability in remanufacturing.

Figure 3-7 Research trends and gaps in I4.0 technologies for remanufacturing

Both low and high value products need to be considered by remanufacturers to support the move towards a CE, but each requires a different, perhaps a matrix style, approach to the processes used. Most of the findings relating to "process" considered high-value assets that form part of a larger system requiring maintenance and servicing, utilising MoL data to support decision-making. In this scenario, it is key that the remanufacturers work closely with the maintenance functions to exchange cores for remanufactured parts, with the potential to provide availability forecasting that can support procurement strategies.

Should MoL data be available, it may assist with failure diagnostics and decisions on repair or replacement (with new, remanufactured or spare) products. In this sector, it is necessary to consider the impact of the remaining life of the host product, the increase and unpredictable failure modes expected with age, the impact of extending product life and the decrease in spare part availability, production data and potential loss of the OEM (Stark *et al.*, 2014) due to their long MoL phases.

Providing relevant and timely MoL data to the people or intelligent systems that require it to support core management is key, but it is necessary first to understand the potentially conflicting data requirements of the stakeholders.

Almost 20 years ago, Coates (2000) recognised the potential for digital technologies to revolutionise manufacturing. The networking of equipment in industry is not new there are opportunities to utilise I4.0 concepts to enhance existing equipment transforming it into smart manufacturing systems (Jin *et al.*, 2017) but this has hardly been demonstrated in remanufacturing.

VR is already used in industry and is being developed to enhance product and process design, optimisation and verification. AR, however, remains mainly in the academic domain, with

questionable value in industry. It has been proposed for training but there were few real-world examples and little evidence to support it as a significant business need. There have been discussions over its use in customer visualisation and customisation (including in textiles remanufacturing (Larsson, 2018)) which may offer some benefits from a socio-economic perspective (Fox, 2016) but its remanufacturing specific application remains unclear. There is a need to further explore the benefits that could be realised using digital twins. 'Product twins' may provide MoL data that could influence EoL activities and 'process twins' could assist in facility design and management should the remanufacturing industry increase its automation capability.

There is sufficient research being conducted on robots in remanufacturing to justify a stand-alone review. Robotics and flexible remanufacturing systems (including real-time adaption) are key to dealing with the variability in demand, product generation, core quantity and quality but their integration into an I4.0 remanufacturing environment is still relatively unexplored.

There are opportunities to apply intelligent algorithms to solve complex remanufacturing problems. Some have already been demonstrated in product selection optimisation and DSP. However, their integration into automated remanufacturing solutions is yet to be fully demonstrated which is key to evaluating capabilities and sharing concepts with technology development partners. Remanufacturing equipment and its monitoring as well as the allocation of processes to assets using the IoT and web-based decision-making algorithms, are likely to operate in a similar way to manufacturing so it would be prudent to remain engaged with those leading this field to understand the infrastructure necessary to achieve such integration.

For remanufacturing businesses to prosper in this new era of connectivity, they will need to invest in ICT and associated support staff that will change the organisation. With the ability to

identify, locate, track and interact with products remotely, it is possible to extract more *value* from remanufactured products, enabling different collaborative business opportunities and solutions (Marconi *et al.*, 2018) that are particularly suited to flexible, highly reactive SMEs (Romero and Noran, 2017). For OEMs who remanufacture their own products, the new structures will need to challenge the long approval cycles to realise the possible technology revolution for remanufacturing (Yeo et al. 2017). As for independent remanufacturing businesses, they will need to develop closer connections with their supply chain utilising ICT to close the gap between their suppliers and customers. Scalable, on-demand cloud systems have the potential to support remanufacturing businesses that experience peak-and-trough demand cycles associated with the lifecycle of the host products. The quality of service from ICT including bandwidth, performance and security remains a concern, but this is not unique to I4.0 and applies to all IoT applications.

Future remanufacturing businesses ought to consider sustainable practices with CE in mind during I4.0 planning and implementing. The expected continued increase in raw material costs will encourage both regulated and non-regulated industries to consider CE principles including remanufacturing and there may well be a shift towards PSS models that remanufacturing will have to support.

Returning to the value creation factors, further research topics are presented in Figure 3-8.

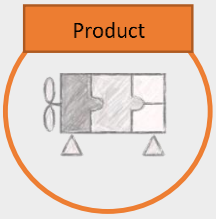
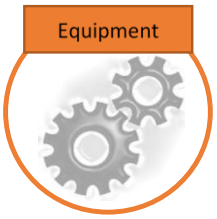
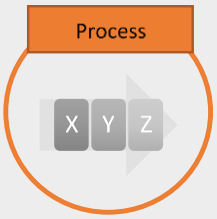
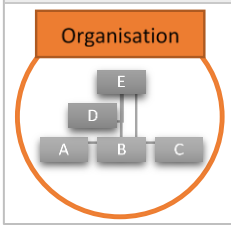
Value Creation Factor	*To exploit emerging digital technology in remanufacturing there is a requirement to:*
	➢ define the information needed at EoL that can be stored on the product at BoL ➢ consider the opportunities of embedded or external DCD ➢ explore the existence of other data storage and transfer devices that could be used ➢ clarify what information DCD should carry in addition to their unique ID ➢ explore the consequences of AM products ➢ define the benefits of combining AM with IoT ➢ align the AM trajectory to support sustainability
	➢ demonstrate AM linked to IoT ➢ develop VR solutions to assist DP, subassembly detection, and destructive disassembly ➢ develop VR solutions to explore disassembly of flexible components, tooling, fixturing, component thermal expansion, contraction and deformation ➢ demonstrate AR using real problems to clarify business need and benefits ➢ explore opportunities to use digital twins for product or process optimisation ➢ demonstrate I4.0 concepts to enhance existing shop-floor equipment transforming them into smart systems ➢ explore reconfigurable systems integrated with IoT ➢ develop specific information collection, advanced data processing algorithms, and information gathering platforms ➢ evaluate the establishment of an EoL database containing reverse logistics information using IoT ➢ expand the research into the use of robots ➢ explore the attributes of collaborative robots for specific activities ➢ demonstrate the application of AI to solve complex problems like robotic DP
	➢ consider the different requirements of low-value, high volume/high-value, low volume products and how this affects the utilisation of IoT ➢ explore how to structure a real-time data-driven optimisation method for production scheduling ➢ define the information required at EoL that can be stored on the product in MoL ➢ explore the automatic identification and capturing of MoL data from the product ➢ evaluate the demand from industry to have BoL and MoL for EoL processing ➢ develop tools and evaluate the use of IoT to estimate and manage remaining life
	➢ explore how I4.0 can support the industry in employing sustainable practices ➢ develop measurements to enable tracking of businesses towards sustainability using I4.0 ➢ explore changes in organisation from linearly connected to networked stakeholders and the new information streams that may be generated ➢ explore the applicability of machine learning and AI in decision-making at management and operations level

Figure 3-8 Further research topics categorised by Value Creation Factor

The factor requiring the greatest focus is 'Equipment' due to its vastness, with a significant need to develop and demonstrate the concepts discussed.

In conclusion, greater automation is required in the currently highly manual remanufacturing processes to enable the utilisation of I4.0 concepts. This will require significant investment in equipment and infrastructure, and the up-skilling of personnel to become competent at interacting with CPS on the IoT. Complete lifecycle data will need to be better understood and remanufacturing processes will need to be modified to utilise it. The IoT will continue to expand with increasing connectivity between AR, VR and shop-floor CPS linked to process and resource control systems, and I4.0 will be realised, taking the remanufacturing industry into the digital age.

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3.10 Published Material Notes and Linking Section

The following information should help the reader understand the link between Chapters 3 and 4 and expands on material that was not published, but deemed relevant, by the author or examiners.

3.10.1 Notes

For clarity, the I4.0 technologies, referenced in Chapter 2, were adapted from Kamble, Gunasekaran and Gawankar (2018)'s sustainability framework as -

- *Internet of Things*
- *Robots*
- *Additive manufacturing*
- *Big data analytics*
- *Cloud computing*
- *Simulation / prototyping*
- *Augmented reality, AR*
- *Advanced materials*
- *Human-machine collaboration*

However, in Chapter 3, when looking specifically at remanufacturing the I4.0 technologies were identified as -

- *Artificial intelligence, big data analytics and robots (Park, 2017)*
- *Internet of Things, virtual reality, and augmented reality (Chang, Ong and Nee, 2017a)*

There is overlap but there are also a few omissions. This is expected as it is the functionality demonstrated by the technologies when integrated that do / do not support the I4.0 principles, not necessarily the 'name' of the individual product. Additionally, as remanufacturing is a smaller sector when compared to manufacturing it can be assumed that many of the technologies in the Chapter 2 list have not yet penetrated mainstream businesses or had their synergies explored specifically in remanufacturing.

3.10.2 Linking Section

Chapter 3 set out a number of further research topics. There was a requirement to define the information needed at EoL that can be stored on the product at BoL and MoL (presented in Figure 3-8) that are taken forward into Chapter 4. This requirement combined with those documented in the 2.9.2 Linking Section led to the exploration of the digital twin (DT) as a way to meet all of these requirements and selected agenda items. DTs had only been on the periphery of the research until this point and had not been covered in detail within the published material. It was therefore necessary to document some background reading on the DT, so Chapter 4 starts of by introducing it as a concept before looking at how it may support remanufacturing going forwards. Whilst not initially recognised as a standalone I4.0 technology in the earlier chapters, it is system that will use them, and with some adaptation, has the potential to be 'smart'.

A GENERIC ASSET MODEL FOR IMPLEMENTING PRODUCT DIGITAL TWINS IN SMART REMANUFACTURING

Submitted original research - technical article.

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M.K. Conceived and designed the article, extracted the requirements, built the model, and wrote the manuscript. D.T.P. supervised the work, supported the execution and interpretation of the findings, critiqued, and edited the manuscript. J.H. reviewed the work and offered guidance on the manuscript.

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4.1 Abstract

A digital twin is a "live" virtual replica of a sensorised component, product, process, human, or system. It accurately copies the entity being modelled by capturing information in real time or near real time from the entity through embedded sensors and the Internet-of-Things. Many applications of digital twins in manufacturing industry have been investigated. This article focuses on the development of product digital twins to reduce the impact of quantity, quality, and demand uncertainties in remanufacturing. Starting from issues specific to remanufacturing, the article derives the functional requirements for a product digital twin for remanufacturing and proposes a UML model of a generic asset to be remanufactured. The model has been demonstrated in a case study which highlights the need to translate existing knowledge and data into an integrated system to realise a product digital twin, capable of supporting remanufacturing process planning.

4.2 Introduction

The optimal process for minimising remanufacturing costs and maximising profits varies with core availability, quality and demand (Liao, Deng and Shen, 2019). Yet, the quantity and quality of returned cores is unpredictable, so the outcome of the remanufacturing operation is highly uncertain (Ondemir and Gupta, 2014). This affects remanufacturing forecasting and operations management (Ilgin and Gupta, 2010). Improving certainty of core quantity (Guide *et al.*, 2000) and quality (Charnley *et al.*, 2019) using through life data is seen as an opportunity to make "smart" decisions on end-of-life (EoL) product processing (Li *et al.*, 2015).

Key smart remanufacturing enablers include cyber physical systems (CPSs), the internet of things (IoT), artificial intelligence (AI) and big data analytics (BDA) (Park, 2017). Using these emerging technologies enables the identification (Schlüter *et al.*, 2018), location (Musa *et al.*, 2014) and determination of the condition (Schmidt, Wang and Galar, 2017) of in-use middle-

of-life (MoL) remanufacturable products and allows for a level of remote interaction (Gu *et al.*, 2017), or EoL processing (Ondemir and Gupta, 2014, Yi and Park, 2015), that has previously been unavailable. This has the potential to extract more value to feed the remanufacturing business (Romero and Noran, 2017, Marconi *et al.*, 2018).

As the IoT can digitally link suppliers and customers (Man and Strandhagen, 2017), it may support remanufacturing providing greater visibility of core availability and quality, reducing reverse supply chain risks (Abubaker *et al.*, 2017). The proliferation of these technologies can enhance remanufacturing forecasting using forward information to alleviate the dual-source uncertainties they face (Goltsos, Syntetos and van der Laan, 2019). Embedded sensors combined with condition monitoring can contribute to management in remanufacturing by reducing uncertainties (Gil-Yong *et al.*, 2018). However, currently, the capturing of accurate, complete and timely whole lifecycle data presents a challenge (Musa, Gunasekaran and Yusuf, 2014), as does effectively mining and utilising this information using big data analytics (Zhang *et al.*, 2017). Currently, data flows generally breakdown once the product is delivered to the user, and during the MoL stage it experiences different operating conditions (Ren *et al.*, 2019) resulting in variance in EoL attributes. Additionally, a level of intelligence and decision-making is required to provide meaningful product MoL information for EoL processing (Musa *et al.*, 2014).

Digital Twins (DTs) are identified as a Gartner strategic technology for 2019 (Panetta, 2018). They combine some of the Industry 4.0 (I4.0) technologies to generate a virtual representation of a product, process or system from inception, through production, to operation (MoL) and finally disposal (Grieves, 2016). DTs have also been proposed to virtually represent operators in human-interfacing CPS (Nikolakis *et al.*, 2019). Interestingly, DTs may be applied to conventional products, processes, people, or systems, but its presence does not necessarily imply or preclude intelligent collaborations.

Whist the definition of DTs and associated standards are still in development (Kiritsis, 2011, International Organization for Standardization, 2019, International Organization for Standardization, 2019, Lee, 2019), industry leaders are already exploring the concept in high-value asset applications such as wind turbines (Dorothy Pomerantz, 2018) and jet engines (Rolls Royce Plc, 2019). However, as the maturity level of the DT concept is so low, there exists many challenges to implementation in this sector (Singh *et al.*, 2018). Additionally, competing, but potentially synonymous concepts battle for research resources including the emerging Asset Administrative Shell (AAS) (Wagner *et al.*, 2017) that forms part of the Reference Architectural Model Industrie 4.0 (RAMI 4.0) (Plattform Industrie 4.0, 2018) and the evolving CPS. Both concepts are subtly different from the DT, but have the potential to be harmonised and integrated to become one and the same (Ribeiro, 2020). It is worth noting that RAMI 4.0 offers an architecture for I4.0 product and process management, based on existing standards, within the production environment (with little to no apparent consideration for products destined for non-production environments). RAMI 4.0 defines the structure that the product or process should exhibit. However, the architecture remains very generalised and provides limited information regarding practical implementation (Langmann and Rojas-Peña, 2016), enabling others to exploit the gaps and offer alternatives (Pisching *et al.*, 2018).

As remanufacturing has a greater chance of success in the same high-value sectors (Yeo, Pepin and Yang, 2017), and assuming more of these entities reach EoL with associated DTs, it may be possible to consider exploiting the DTs for remanufacturing purposes, as suggested in previous reviews (Kerin and Pham, 2019). What is clear is that production planning and control in remanufacturing is more complicated to manage than in manufacturing (Guide *et al.*, 2000). There is also a general expectation that the assessment, measurement, capturing, modelling and presenting of product health and degradation information through advanced technologies that support life extension strategies (Roy *et al.*, 2016) could be leveraged (Gao and Wang, 2017,

Kerin and Pham, 2020). To target the unique issues faced by the remanufacturing industry, it is necessary first to understand them.

Following a literature review to highlight issues with uncertainties in remanufacturing and the potential to use DTs to mitigate them, this article will determine the functional requirements for a DT fit for high-value asset remanufacturing and propose a DT model of a generic asset expressed in the UML modelling language. The article will conclude with a case study to demonstrate an application of the proposed model and identify where it could be improved.

4.3 Literature Review

Research in both DTs and smart remanufacturing is in its infancy. DT are identified a leading I4.0 technology (Panetta, 2018) that, in turn, can be used to promote a circular economy (CE) (Pagoropoulos, Pigosso and McAloone, 2017). Growing attention is being given to both DTs (Diez-Olivan *et al.*, 2019) and smart remanufacturing (Kerin and Pham, 2019), this is generally pursued separately. Only two articles contained both key words and they were unique in their application and focus. Wang and Wang (2019) used the DT concept specifically for the recycling, recovery and remanufacturing of waste electrical and electronic equipment, whilst Scott-Emuakpor *et al.* (2014) investigated material and geometric properties of fatigued alloys to populate DTs for the remanufacturing of aging aircraft components. A gap in the literature calls for the synergy of remanufacturing and DTs. As DTs are so new, this work will start with understanding the more established remanufacturing operation in more detail.

The complications in production planning and control for remanufacturing over manufacturing relate to several issues including:

- uncertainty in timing and quality of returns
- the need to balance returns with demand

- inherent issues found during the disassembly of returned entities
- uncertainties in materials recovered from returned items
- the requirement for a reverse logistics network
- complications of material matching restrictions
- problems of stochastic routings for materials for remanufacturing operations leading to highly variable processing times (Guide *et al.*, 2000)

Current manually-based data acquisition approaches, widely used during asset recovery only, are inaccurate, and untimely, so decisions based on such data are usually ineffective (Ren *et al.*, 2019).

4.3.1 Timing and Quality of Returns

Research suggests that through implementing emerging technologies the timing of returns can be incentivised (Matsuyama, Fukushige and Umeda, 2015), encouraged and even managed (Ullah and Sarkar, 2020). The timing of returned cores is dependent on a number of factors including sales profile, life expectancy, MoL utilisation, the host environment and life-extension activities (Stark *et al.*, 2014). Other factors include the articulation of actions taken by entities themselves based on their awareness, perception, intelligence and extroversion of their environment (Romero and Noran, 2017). The approach taken by the OEM or remanufacturers to manage, (or not) the returns profile also affects the quality of cores available (Wei, Tang and Liu, 2015) and subsequent profitability (Guide, Teunter and Van Wassenhove, 2003). Currently, before (proactive) or after (reactive) the cores arrive at the remanufacturer, quality classification is conducted to determine remanufacturability and to facilitate purchasing (Figure 4-1).

During the life of high-value entities, advancements in technology will occur whereby more efficient offerings will become available. The difference between the two will affect the entities

life expectancy (Westkämper, 2003). The application of life extension techniques on only some components within a host asset is associated with an increase in unexpected / unpredictable failure modes, issues with spare parts availability and loss of original manufacturing data, further complicating EoL timing and quality predictions (Stark *et al.*, 2014).

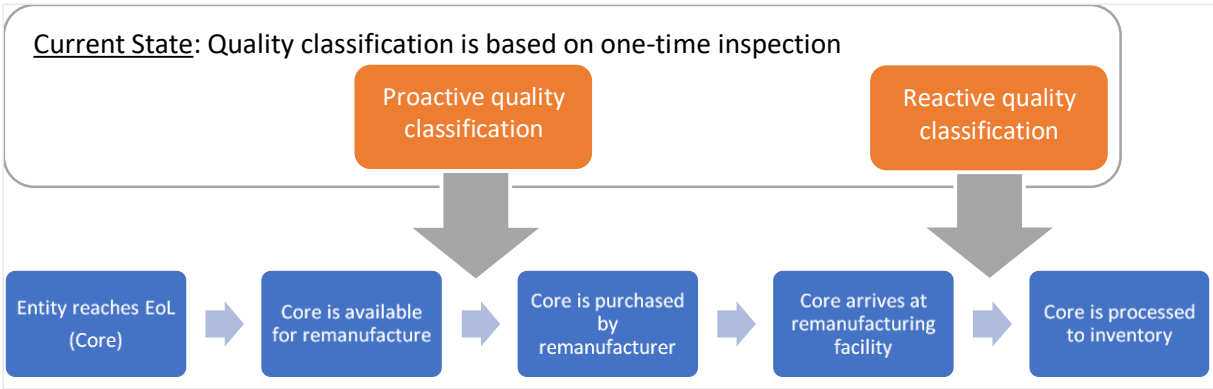

Figure 4-1 Current quality classification methods used in remanufacturing

4.3.2 The Need to Balance Returns with Demand

The demand profile for the remanufactured entities is also volatile, affecting core inventory planning and acquisition (Xie *et al.*, 2015). A high demand can allow remanufacturers to increase the selling price but against a low supply it can force them into processing more cores of inferior quality, increasing costs (Liao, Deng and Shen, 2019). Contrastingly, low demand and high returns generally offers better quality cores but ties up cash in inventory. Influencing factors include the sequence of processing the cores of different quality classification (Liao, Deng and Shen, 2019), changes in the condition of existing in-use entities (deterioration etc.), core availability, market behaviour, and the changing needs of the customers or society (Takata *et al.*, 2004). This is further complicated in mixed or hybrid manufacturing and remanufacturing operational environments (Wei, Tang and Sundin, 2015, Assid, Gharbi and Hajji, 2019) where the impact of returns can affect the provisioning for the next generation in terms of volume and quality (Matsuyama, Fukushige and Umeda, 2015), and when the capacity and capability of the facility is overlaid (Guide, Teunter and Van Wassenhove, 2003).

4.3.3 Issues Found During the Disassembly of Returns

Disassembly is a significant step in the remanufacturing process (Priyono, Ijomah and Bititci, 2016). The level of disassembly can vary from partial to complete performed using destructive or non-destructive methods (Touzanne, Henrioud and Perrard, 2001). However, there are several factors that influence the disassemblability of an asset (Desai and Mital, 2003) that may not be recognised until the process is underway. These include the solidification of supposedly removable fasteners (Mullo *et al.*, 2019), wear or cross-threaded components. Other potential hurdles that may or may not be recognised before the process commences include one-way fittings, the use of welded joints or adhesives, and modifications made to the asset during the MoL phase.

Disassembly using robots is a growing research subject (Zheng *et al.*, 2017) but additional functionality is required to deal with the issues found in-process. Researchers have proposed smart (Kagermann, 2013), reconfigurable (Koren *et al.*, 2018), collaborative (Chen, Wegener and Dietrich, 2014, Wegener *et al.*, 2015, Huang *et al.*, 2019, Liu *et al.*, 2019) and moveable (Fox and Richardson, 2017) factories to manage these uncertainties, however, robotics in remanufacturing and automated testing before disassembly is not commonplace. Pre-disassembly testing can be performed to minimise the risk of finding issues later in the remanufacturing process. Multi-level inspection cells that contain highly automated testing and scanning equipment (Stark *et al.*, 2014), combined in some cases with additive manufacturing facilities (French, Benakis and Marin-Reyes, 2017), have been proposed. Structural integrity of components can also be assessed using ultrasonic inspection methods (Tant *et al.*, 2019), however issues are generally identified during a predominantly manual inspection process (Desai and Mital, 2003), and are dealt with on a case-by-case basis.

4.3.4 Uncertainties in Materials Recovered from Returns

Intellectual property rights can be a barrier to obtaining asset data that can be used to facilitate remanufacturing (All Party Sustainable Resource Group and the All Party Parliamentary Manufacturing Group, 2014). This barrier is even higher if the remanufacturers are not partnered with the OEM (Hartwell and Marco, 2016). Without this information cores can still be processed but the level of uncertainty in the properties of the materials contained within the product can be high.

The state of the materials recovered from returns will be dependent on the core quality, and MoL component exchanges / upgrades. However, the material type depends on the components original manufacturing process. Knowing this information is particularly important if the asset contains hybrid materials or structures (Rejeski, Zhao and Huang, 2018).

4.3.5 The Reverse-Logistics Network

Successful management of the reverse supply chain is one way to improve customer perception and loyalty (Statham, 2006, Kumar, 2016, Gaustad *et al.*, 2017). It can also play a large part in the profitability of opportunistic 3rd party remanufacturers (Abbey and Guide Jr, 2018). The recovery or purchasing of core and its disassembly, forms a large part of this network but the design of this system depends on the remanufacturing strategy, the original design philosophy, incentives and legislative drivers (Abbey and Guide Jr, 2018).

Other uncertainties that affect the reverse-logistics network include the state of the asset and its whereabouts with respect to the remanufacturing facility (Tornese *et al.*, 2018). In order to recover the asset, there needs to be a trigger to start the process that makes the remanufacturing agent aware of its availability and location (Wang *et al.*, 2014). Once on-site, the management of cores remains a challenge and the tracking of the disassembly through the process needs to be optimised and controlled (Zhang *et al.*, 2015).

4.3.6 The Complications of Material Matching Restrictions

Second generation entities can be formed from multiple cores and multi-parameter evaluation metrics have been proposed aimed at identifying the best EoL asset to remanufacture (Meng *et al.*, 2016). The tracking of components from an asset through the remanufacturing process is also desirable (Uhlemann, Lehmann and Steinhilper, 2017) however, ensuring traceability is particularly important in remanufacturable safety critical entities like battery packs (Harper *et al.*, 2019) or aircraft engines (García-Alcaraz *et al.*, 2019). In the aerospace industry, where identicality and functionality of the remanufactured asset must be proven, a higher level of testing and certification process is applied (Scott-Emuakpor *et al.*, 2014) making the material matching, tracking and labelling more complex.

4.3.7 Highly Variable Processing Times

Due to the issues discussed in section 4.3.1-4.3.6, there is great variability in remanufacturing routings and processing times. As soon as an asset reaches EoL its routing is likely to differ as its location and state will drive different reverse logistics or disposal requirements (Wang *et al.*, 2014). Once at the remanufacturing facility, the objective (to remanufacture-to-order or disassemble-to-order etc.) will also drive different solutions (Ondemir and Gupta, 2014).

The disassembly process, whether it be manual or automated, smart or otherwise, needs to be planned with its optimisation being a popular topic (Wang *et al.*, 2013) and on-line re-planning may be beneficial (ElSayed *et al.*, 2011). However, the stochastic nature of the volume and quality of the returns makes fully automated disassembly challenging (Vongbunyong, Vongseela and Sreerattana-aporn, 2017). The remanufacturer can aim to minimise the variability or allow it to exist and install flexible solutions (Huang *et al.*, 2019), but much of this is currently performed manually, in-process, by the operations team which is why the process times are highly variable.

4.3.8 The Digital Twin

There is growing interest in the fusion of sensors and data to form DT (Diez-Olivan *et al.*, 2019) for products (Potting, 2016), people (Nikolakis *et al.*, 2019), or processes (Uhlemann, Lehmann and Steinhilper, 2017) in manufacturing that can be applied to remanufacturing (Goodall, Sharpe and West, 2019).

The DT concept first proposed in the early 2000's comprises three main elements (Figure 4-2):

- a real product in real space
- a virtual product in virtual space
- the connections of data and information that tie the 'products' together (Grieves, 2014).

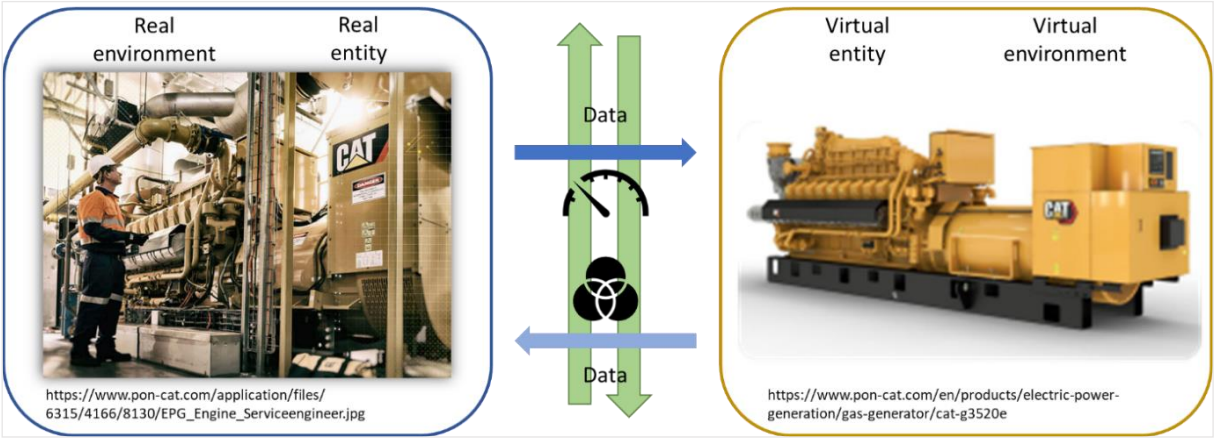

Figure 4-2 The three elements of a Digital Twin

This has been expanded and DTs can now represent individual components, products (assets), operators, systems or processes (GE_Digital, 2018) referred herein as "entities". They can also be combined depending on the insight required, e.g. product and production processing data can be leveraged to represent operational performance (Siemens Industry Software Inc., 2019). NASA justified the need to develop DTs in 2012 for advancing fleet design and management through virtually mirroring the life of the real aircraft, describing the DT as an integration of ultra-high-fidelity simulations with the aircrafts on-board health management system,

maintenance history and all available historical and fleet data (Glaessgen and Stargel, 2012). In summary, the DT structure relies on connectivity to the real asset, where local systems perform condition monitoring and management considering the immediate environment, where real-time performance data is collected and fed into simulation tools and or, storage for performance predictions calculations and historic analytics, respectively. The data store can also accept fleet data for analysis of the real entity with others in the field (Figure 4-3).

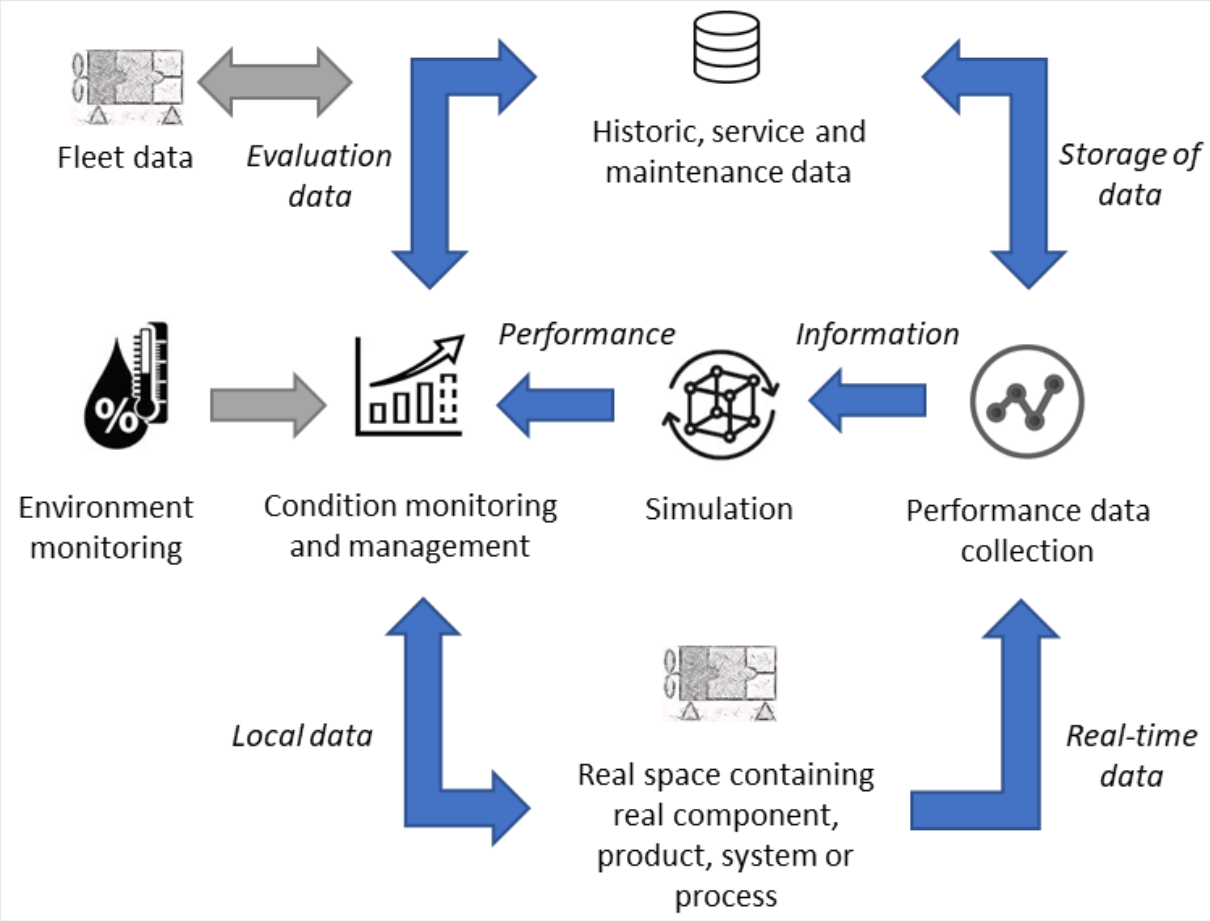

Figure 4-3 Data flows in a basic Digital Twin

With the exception of people, the real and virtual assets are expected to be connected from creation, to manufacturing, through in-use operation and finishing at EoL (Grieves, 2016) forming a through life digital thread (National Institute of Standards and Technology - U.S. Department of Commerce, 2014). DTs can exist as a single instance corresponding to a specific

asset (DTI), an aggregate of similar entities (DTA), or an environment (DTE) applicable to both the DTIs and DTAs depending on its purpose (Grieves, 2016).

In summary, different strategies to mitigate the uncertainties in remanufacturing have been explored but findings suggest these are generally visionary. Additionally, to date, no tool has been designed, proposed or recognised as a solution (García-Alcaraz *et al.*, 2019). The AAS from RAMI 4.0 has been described by some as a DT, but it remains immature. The term 'digital twin is referenced only once in the standard (Plattform Industrie 4.0, 2019), lacks implementation detail and is focused on manufacturing industry based equipment, processes and systems only.

There are many benefits to be had from enabling asset visibility throughout its lifecycle. In remanufacturing these are associated with planning and controlling operations and assessing an entities suitability for processing (Musa, Gunasekaran and Yusuf, 2014). There does not appear to be any research published on leveraging DTs to resolve some of the uncertainties in remanufacturing, and there is a clear requirement to demonstrate the benefits of I4.0 for this sector. It is for these reasons that DTs as potential solutions will be explored to reduce uncertainties in high value asset remanufacturing planning and control.

4.4 Requirements for DTs in High-Value Asset Remanufacturing

This section defines the functional requirements for DTs to reduce the impact of the challenges found in remanufacturing. Section 4.4.1 derives boundary conditions and assumptions from the information presented in section 4.3.8. Section 4.4.2 translates the findings from the literature review (sections 4.3.1-4.3.7) into high-level requirements and discusses how they may be fulfilled with respect to product life cycle management. Section 4.4.3 considers the need for instantaneous digital instances and section 4.4.4 allocates out the requirements to develop a simple UML model of a generic asset.

4.4.1 Asset Criteria

There is a base level of technical capability needed from the asset to support the generation of associated DT. Similarly, there are certain requirements from the initial manufacturing process needed to populate the early life of the DT. It is therefore necessary to define some assumptions that are made about the asset to be remanufactured. The assumptions based on the findings in (Kerin and Pham, 2019) are as follows:

- the asset to be remanufactured has been designed using CAD techniques, manufactured using processes that provide digital in-process verification measurements and are tested to applicable standards.
- the asset to be remanufactured is sensorised and key performance indicators are monitored.
- the environment in which the asset is utilised is controlled (and is known) or is also monitored with data available to reference.
- that some form of connectivity to the internet is available once the asset has been manufactured (towards the end of its BoL phase), but before it reaches the customer, and during the MoL and EoL phases.

With these capabilities, an asset can be considered a candidate for digital twinning, but the detailed requirements and how they may be fulfilled, are yet to be defined.

4.4.2 Translating High-Value Asset Remanufacturing Issues to Requirements

The basic requirements of the DT, extracted from section 4.3, are presented in Table 4-1. Categorised by issue, each of the 16 requirements have been given an ID and a short explanation of what they would enable. Whilst the requirements would need to be fully completed by the time the product reaches remanufacturing, some can be attained early in the product's life and remain static, whilst others will need to come later and may need to be dynamic.

Table 4-1 Summary of requirements for DTs to support remanufacturing

Issue	ID	Requirement	Enable
Timing and quality of returns	a	To understand the quantity and quality of the entities in the field	The visibility of MoL status and performance
	b	To predict when an asset is likely to require remanufacturing	An estimate of remaining useful life
	c	To understand the quality of the asset during MoL and at EoL	An asset quality metric
The need to balance returns with demand	d	To understand the profile of potential returns considering the original sales volume	Visibility of the quantity and quality of entities in MoL at customer, and at EoL in remanufacturing stream
	e	To improve demand and opportunity forecasting	Visibility of future entities that share components with the current generation
	f	To support proactive remanufacturing operations planning	Mapping of core requirements against facility capacity and capability
Issues found during the disassembly of returns	g	To understand the quantity and type of components and fastening methods used in the asset before processing	Access to the original CAD models and BoM
	h	To identify potential disassembly issues before the process starts	Visibility of the as-built in-process verification results
Uncertainties in materials recovered from returns	i	Ensure MoL service / upgrades are visible and to enable rectification / AM process success	Access to the latest BoM containing component material level data
The reverse-logistics network	j	Proactively manage core collection	Location and readiness of the of asset when it reaches EoL
	k	Track through the remanufacturing process and to allocate data	Unique identification of entities
The complications of material matching restrictions	l	Enable multiple generations of parts to exist in the same product	Uniquely identify remanufacturable components within an asset
	m	Ensure alignment with the real asset through multiple life cycles	Enable the “remanufacturing” of the digital asset
	n	Support functionality testing	Access the entities original as-shipped performance results
Highly variable processing times	o	Virtually plan and manage routings based on core quantity and quality data	Access to a remanufacturing facility model
	p	Optimise disassembly sequence	Disassembly process simulation results

Mapping the requirements against a closed-loop product lifecycle offers an insight into where the information to fill them can be found (Figure 4-4). The BoL, MoL and EoL stages are also shown for clarity in discussion.

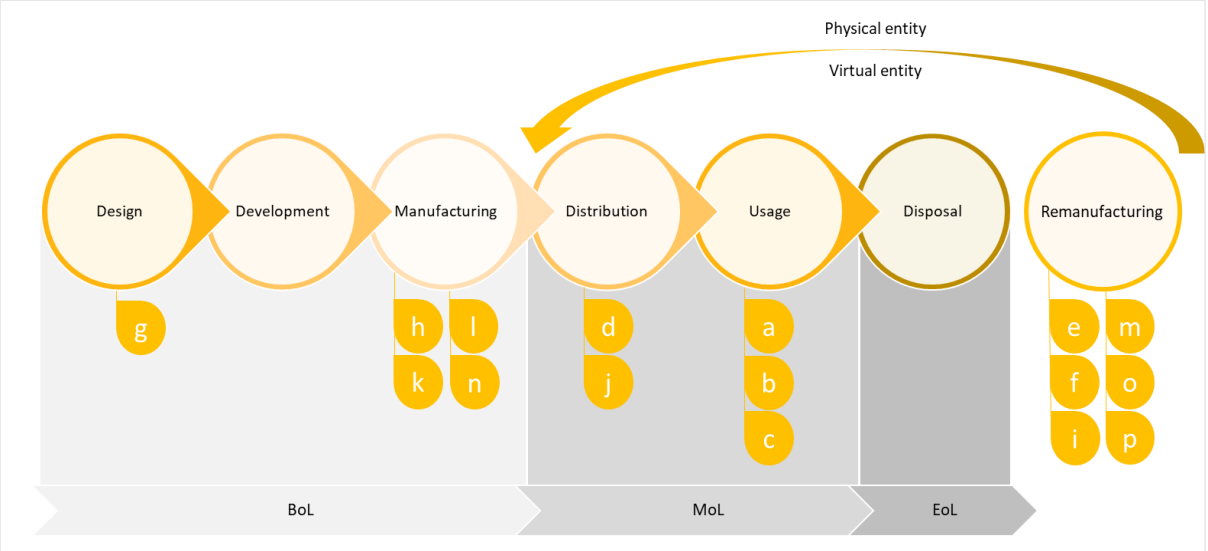

Figure 4-4 Assignment of requirements for remanufacturing to different PLM stages

At the BoL, the product type CAD and engineering BoM (eBoM) can provide asset design information at component, sub, and complete assembly level, useful for remanufacturing process design. Model order reduction may well be needed to balance accuracy, accessibility and speed for real-time connectivity and decision-making (Hartmann, Herz and Wever, 2018) but at least the baseline information already exists. Additionally, the manufacturing BoM (mBoM) and as-built data provides information on the realised, uniquely identifiable, asset and its components. This is necessary as it captures deviations within tolerances and non-conformance entities that have been processed with waivers.

Examples of useful information include, as-machined geometry for component repair (Kim *et al.*, 2019), originally applied torques for implied unscrewing requirements (Liu *et al.*, 2019) and key product characteristics to manufacture / purchase replacement parts (Zheng *et al.*, 2008). The as-shipped performance results (from physical tests or simulation) may be obtained (from OEM PLM, MES or similar database) to support remanufacturing expectation limits for functionality assessment. The real asset will be connected to the IoT before being released to the marketplace with its DT (stored locally or remotely) already populated with its BoL data.

The unique identification of the core and the remanufacturable components within it, is necessary to enable monitoring and processing through remanufacturing. Serialised RFID is a popular solution to store the ID (Musa *et al.*, 2014, Li *et al.*, 2015) but there are other methods that deserve consideration including basic 2D codes through to more advanced self-sensing tags (Xu *et al.*, 2017). Either way, the unique ID, issued during manufacturing, will be linked to metadata that describes the asset and supports the evaluation of its performance against others in the field. To accurately evaluate, the existence and location of the entities in the field can be made visible during distribution.

Once in-use the asset needs to be connected to the IoT to emit status, performance, and residual life estimates. Useful in this domain is the asset quality metric, key to evaluating remanufacturability. There is growing tendency to use data recorded in electronic devices to form part of a remanufacturing pre-inspection process but this is still rare (Gao, Xing and Marwala, 2013). These can be used to estimate remaining useful life that in turn can indicate quality (Ondemir and Gupta, 2014), but generally, the metric comes in the form of a quality classification bestowed on the asset following a physical inspection at EoL (Wei, Tang and Sundin, 2015). Typically the classes are pre-determined, and the inspection process is assumed to be perfect, however, the classification methods themselves depend on the quality distribution, and human errors are inevitable (Wei, Tang and Sundin, 2015). Consequently, this mismatch has led to the development of a 'certainty of product quality' (CPQ) metric, populated using MoL data captured from sensors providing visibility of status, performance quality and quantity to support confident data-driven decision-making (Charnley *et al.*, 2019).

Location, and or, readiness of the of asset when it reaches EoL can be supported by the integration of RFID tags and sensors read by mobile data systems Wi-Fi or GPS to support traceability of return flows (Li *et al.*, 2015, Garrido-Hidalgo *et al.*, 2019) or inventory through the remanufacturing process (Zhang *et al.*, 2015, Zhang *et al.*, 2018, Li *et al.*, 2019). The asset

locating data can flow into the DT to allow for earlier purchasing and process management decisions.

For EoL processing the most recent BoM is required but this is not necessarily the original mBoM. Changes may have occurred during MoL utilisation. (Lejon and Jeppsson (2015) propose a concept that enables MoL information to be integrated to a virtual product representation within TeamCenter PLM.) Access to the most recent BoM can help formulate a service BoM, the process of which could be applied to the development of a remanufacturing BoM (rBoM) (Zheng *et al.*, 2017). Depending on the level of remanufacturing expected, the component level content of the asset may be enough. However, the release of sub-assemblies for secondary processing and coordination with purchasing becomes complicated and where component repair through subtractive, additive or hybrid machining methods is expected, material level data would have to be available to be truly beneficial without the need to employ reverse engineering techniques.

Once an asset has reached its EoL, its DT can be updated to reflect this. Some aspects of the DT may enter a state of suspended animation at this point, as in-use data is no-longer generated. However, it would be beneficial to retain frequently updated location information at least up until a decision has been made on how it will be processed. If the asset is disposed of, then the DT can also be deleted (unless a viable EoL use for the data is also established (Okorie *et al.*, 2018)). However, if the asset is to be remanufactured, the reverse logistics network needs to be utilised to recover it and the DT needs to be saved.

Making the manufacturing Bill of Process (BoP) available at the entities EoL may not help remanufacturing routings. As the process of remanufacturing includes both disassembly and assembly operations, the remanufacturing BoP (rBoP) is significantly different to the manufacturing or reverse assembly BoP. The potential for selective or partial disassembly

processes also drives different equipment requirements, and applications. However, disassembly process planning required to formulate the rBoM and rBoP would benefit from information that describes the relationships between components within the asset (Liu *et al.*, 2018) and the as-built data (previously described), along with a current state remanufacturing facility model. This would allow mapping of the core's requirements against the facility capacity and capability and to allow disassembly simulations to be analysed (Chang, Ong and Nee, 2017a). The real remanufacturing process can also be represented as a DT updated with real-time information (Uhlemann, Lehmann and Steinhilper, 2017, Yeo, Pepin and Yang, 2017). However, issues found during the disassembly process are complex making it difficult to develop specific elements of DT to assist. Tightly linked material physics level DT may offer some support, but current CAx systems struggle replicating material warping and fastener solidification etc. Adaptive geometry modelling is being developed to allow nominal models to be updated with measured data (Praniewicz, Kurfess and Saldana, 2018) but assessing material level change is not practical when the asset is in-use. Furthermore, sensorising the real asset to feed back this data, is equally challenging. This limits the impact of the DT in reducing disassembly uncertainties. Looking further afield, visibility of future entities that share components with the current generation could be useful to predict demand, as big data systems offer tools for fusing diverse information streams, improving forecasting for remanufacturing (Kusiak, 2015).

4.4.3 The Need for Instantaneous Digital Instances

At every stage of the asset's life there is a need to update the virtual twin to match that of the real one. However, as can be seen from the previous section, current state information alone is insufficient. There is still a need to access data from previous key points in the asset's life. For example, should a DT be sufficiently advanced to reflect a worn valve seat in a cylinder-head assembly, without the original as-built data an alternative method of identifying the need for

metal deposition and/or machining will need to be found to remanufacture the part. Additionally, BoL data can be used by remanufacturers to ensure they supply an asset that meets the definition of "remanufactured" by matching or surpassing "as-new" performance. This may be best managed by a set of digital instances (siblings) that reflect the real asset (current state), previous, simulated, and potential future states. The digital siblings can remain in a suspended state, without modification, to be called on at EoL (Figure *4-5*). This way remanufacturers have visibility of the previous state, current state, and potential future states of the asset whether that be a component, product, system, or process.

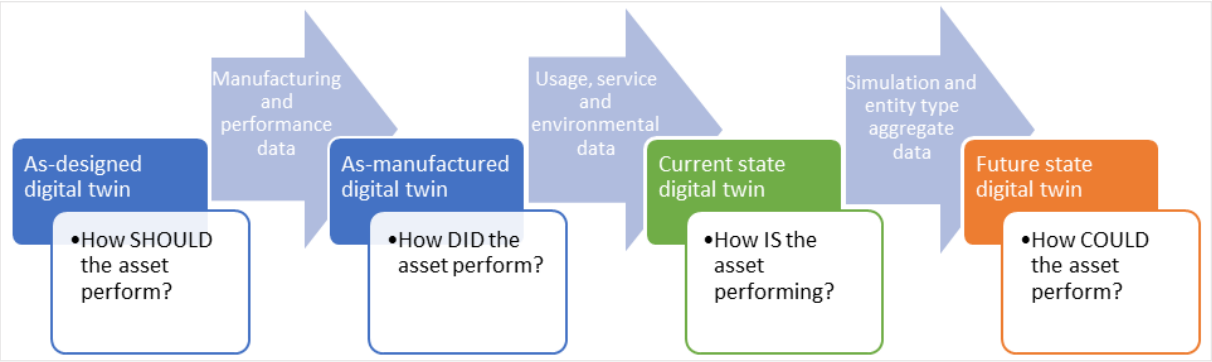

Figure 4-5 Digital instances that need to remain in a suspended state for remanufacturing

4.4.4 Assignment of Digital Twin Requirements

Component and product DT can be combined, just like their real counterparts to form an aggregate process or system DT. It is therefore advantageous to set boundaries for future work by distributing the requirements between those that best relate to the component / product, or system / process level DT. It should be recognised that some cross-over is expected and will be scenario and environment dependent. Taking inspiration from Goodall, Sharpe and West (2019), Kiritsis, Rolstadas and Moseng (2008) and Singh *et al.* (2019), a generic asset and the DT remanufacturing requirements are modelled using a Visio UML class diagram (Figure 4-6). The model is developed based on the information gathered from the literature review and

following an iterative design process when applied to the case study. The attributes and relationships of the model are described below.

Figure 4-6 is divided into three sections, level 1 'real', level 2 'virtual' and level 3 'process'. The classes in level 3 process show key remanufacturing process functions that are likely to pre-exist. As a result, the attributes and operations for each class have not been defined. In summary, labour (*Human_Resource*), materials (*Material_Resource*), and equipment (*Equipment_Resource*) combine to form the remanufacturing resources (*Resources*) with a mixture of attributes reflecting skill levels, availability performance and quality. Not all resources are required, but to add value to the core there needs to be at least one. The capability (*Real_Reman_Capability*) is exclusively dependent on these resources. The capability of the facility is also a function of the process that has been established (*Real_Reman_Process*) at the current time and location (*Reman_Time_Location*), the capacity (*Real_Reman_Capacity*), which is itself a function of the current work-in-progress (*Reman_WIP*). The process and the remanufacturing BoM (*Reman_BoL*) are related, both dependent on the requirements of the inbound core (*Reman_Core*) and demand (*Demand*).

The classes in level 1 real, towards the bottom of Figure 4-6, also represent likely pre-existing remanufacturable product functions. However, identified attributes have been defined as they are needed for upstream processing. All attributes are denoted as public at this stage. High-value products go through detailed design iterations, but when the product is manufactured it is done so to a standard set of requirements (*As_Designed_Entity*). The *As_Designed_Entity* class needs to be identifiable and specific to the remanufacturable asset. As previously described, CAD, BoM, test specifications (*Test_Spec*) and operating limits (*Operating_Limits*) can be useful to remanufacturers but so too could the asset manual (*Manual*), the details of interfaces and connections for test processes (*Test_Interfaces*), a list of fluids, lubricants, oils, pneumatics settings used (*FLOPS*), the related material safety data sheets (*MSDS*), any software details

(*Software_Spec*) and the identity of the parent parts the child entity could belong to (*Compatible_Parent_ID_Type*).

The class *As_Built_Entity* derives from the *As_Designed_Entity* and reflects the specific assembly details of the entity *Real_Entity*. The key attributes from this class needed for remanufacturing include characteristics (critical or special) and test results, details of any deviations (*Approved_Deviations*) from the *As_Designed_Entity* and specific details like firmware level etc. The class *Real_Entity* exists to represent the physical asset in its current state with attributes relating to its release date (approx. start of MoL), the entities parent part (*Parent_ID*) if applicable, and when it became associated with the parent (*Child_of_Parent_Since*). This becomes relevant if an asset has been modified from the *As_Built_Entity* state and is now a hybrid assembly (i.e. MoL maintenance activity). Every *Real_Entity* has a unique ID (*Real_ID*) and an *ID_TYPE*, necessary to communicate the format method (human-readable, RFID, QR etc.). They could belong to many groups (*Entity_Groups*) that are made up of entities that have the same *As_Designed_Entity* attributes, generally referred to as 'product type' or 'family' in industry.

As already described, for an asset to support a DT, it needs at least one sensor (*Sensor*). The attributes of the sensors need to be well defined to assess accuracy of measurement and confidence at both instance and aggregate level DT, whist *Sensor_Data* provides the value (*Sensor_value*) and associated timestamp (*Meas._Timestamp*). Both the current time and location (*Entity_Time_Location*) feeds the information related to the asset in its current state (*Current_Status*) that itself contains an incarnation attribute (*Incarnations*) to capture the number of life cycles the asset has been through previously, its status (*Status*), e.g., operational, stand-by, offline, unserviceable etc. and its readiness (*Availability*) for remanufacturing. Completing this section, modification to the asset during MoL is captured in *Field_Activity* for the events triggered by servicing, maintenance or user reconfiguration, or in

In_MoL_Mod_Entity for self-adjusted (where the asset makes changes to itself). Both classes support the changes that will occur in the *Real_Entity* following the modification / reconfiguration and do so by capturing a timestamp and description. Additionally, *In_MoL_Mod_Entity* contains three Boolean attributes, *DMM_Init._Activity* and *Field_Init_Activity*, that indicate whether or not the self-adjustment was enacted as a result of decisions made in the virtual environment (*Decision_Making_Module*) or the field activity respectively, and *Auto_Release* that defines whether the change activity was managed solely by the asset or involved secondary, probably human, approval and release.

The final middle section (level 2 virtual) functions in the digital world. It takes information from both the real asset and remanufacturing business, evaluates it, and then makes decisions on future activities. Starting with the digital, exclusive representation of the real asset, the *As_Built_Entity* combined with the *Field_Activity* data flows through the *Real_Entity* to populate the *Virtual_Entity*. Each virtual asset will require a unique ID (*Virtual_ID*) that would benefit for being linked to *Real_ID*. From the data available at this stage, different simulations (*Entity_Simulation*) can be triggered with the relevant simulation parameters (*Sim._Parameters*). The results from the simulations (*Sim._Results*) can formulate a vision and estimate of the future state (*eFuture_State*). Key predictions for remanufacturing process management include an estimate of RUL (*eRUL*). This drives the predicted EoL date (*eEoL*). An estimate of quality (*eQuality*) and failure mode (*eFailure_Mode*) at *eEoL* are linked and may be possible simulation outputs. The estimation of quality at EoL may not always be zero as the failure mode may affect only part of the product. For example, a piston seizure can cause a catastrophic failure and unrecoverable engine, however a valve seizure is likely to need only a cylinder head replacement making remanufacturing a more realistic proposition. Errors in accuracy, precision and resolution of the measurements taken by the sensors, those embedded

in the virtual models and simulation algorithms amongst others need to be appreciated. This warrants a confidence level attribute (*EoL_Confidence*) at this class.

The *eFuture_State* class can offer an insight into the potentially recoverable parts of the asset. *Virtual_Core* takes this information and extracts the associated parts from *Virtual_Entity* to generate a virtual core that can be utilised to assess remanufacturing BoM, processing and resource requirements, opportunities, and risks (*Reman_Opportunities*). These can be assessed through the normal channels. Alternatively, the virtual core could be pulled into a process simulation (*Process_Simulation*) to assess the same, with a decision-making module (*Decision_Making_Module*) that considers the outputs of the future state estimates to feed into the *In_MoL_Mod_Entity* enabling asset self-enlightenment and adjustment, with the aim to balance RUL with remanufacturing optimisation. The *Decision_Making_Module* can utilise the fleet data to trigger the most relevant simulation to run in *Entity_Simulation*.

The UML Class diagram has been formulated from the DT requirements. To illustrate its potential and to identify areas of improvement, a preliminary case study has been conducted as reported in the next section.

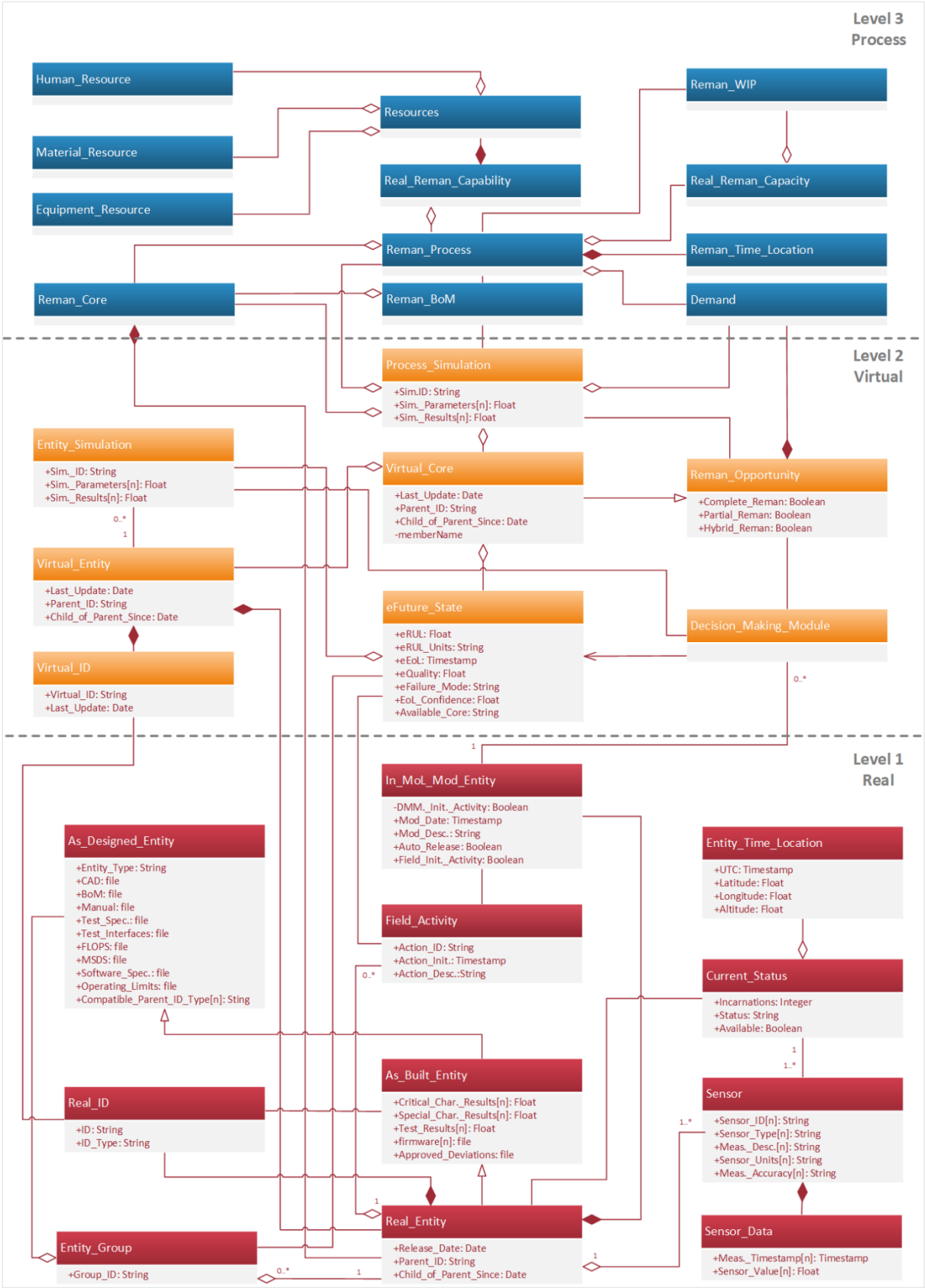

Figure 4-6 UML class diagram model of DT enabled asset in remanufacturing

4.5 Case Study

This section utilises a real case study to analyse the applicability of the proposed model and to identify areas where it could be improved.

4.5.1 Case Overview

With a global footprint, company A employs over 100k people and generated USD53billion in global sales and revenue in 2019, supplying products and services in construction, power generation and transportation. With over 1million connected assets it already utilises internet-based support systems and encourages sustainable and circular business practices including remanufacturing.

Large industrial and off-road engines form part of the company's portfolio. They tend to have long life spans, meet the basic asset criteria defined in section 4.4.1 and fit the high-value asset description that is the focus of this work. With design, development, manufacturing, and remanufacturing facilities in the UK this company offers an applicable, local insight into current OEM practices that could be leveraged. It is therefore possible to evaluate the model by overlaying the pre-existing product attributes and business systems.

4.5.2 Model Implementation

The manufacturing and remanufacturing functions exist in different locations and parts of the business. This makes the sharing of relevant information more complex. Additionally, it was not possible at this stage to use the same engine product that is currently being designed and manufactured in one facility, as that being remanufactured in the other, to form the case study. Instead, two different products have had to be used from the same company, and an assumption made that that the high-level manufacturing process and remanufacturing process are the same for both products. The model is populated with example data from both the manufacturing and remanufacturing functions (Figure 4-7).

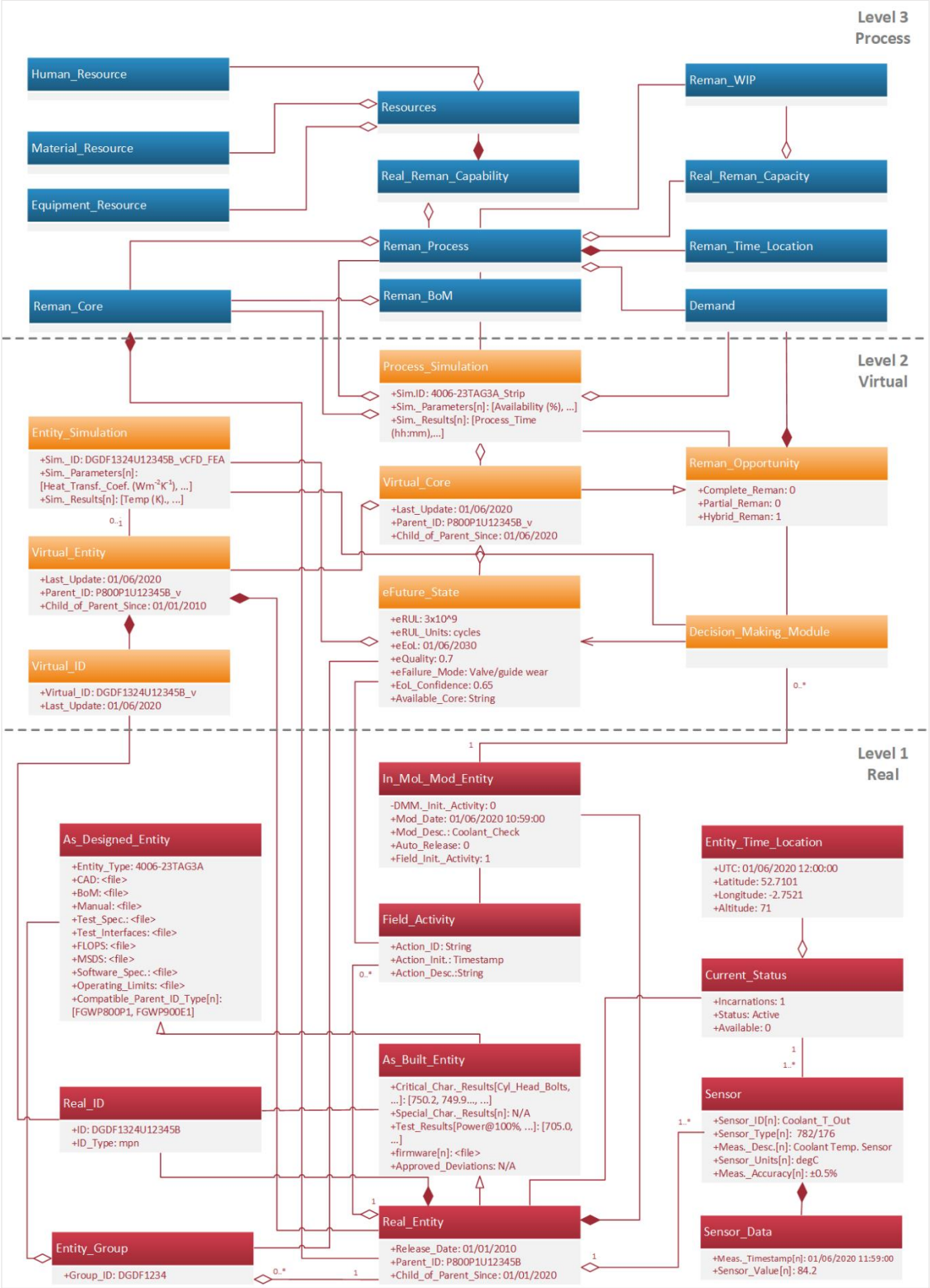

Figure 4-7 UML class diagram model of DT containing case study information

Starting with the product design (*As_Designed_Entity)*, each product does belong to a family (*Entity_Group*), referred to as the 4006-23TAG3A. Design activity occurs in Creo (formerly Pro-Engineer). This package allows for structural, thermal, and modal analysis on 3D CAD designs in the same environments. In parallel with development, the product manual, testing, and operating requirements are defined and managed using internal quality systems and ISO 9001:2015. This product can be installed in many different systems, but a popular compatible parent product is the P800P1.

The *As_Built_Entity* data can be populated from the manufacturing execution system (MES) that manage the semi-automated assembly lines. All critical and special characteristic torques are applied using monitored tooling, results are captured and available for post processing or querying. Similarly, test results, certificates and deviation approvals are available in the quality management system (QMS).

Each product is released to the build-line with its own unique ID, generated from the family, order number, manufacturing location and year of manufacture information. This is available on the data-plate as human-readable only. (RFID chips in bolt heads fitted to the products are used in some facilities to allow process data transmission, but most in-service products have only the data-plate.) Some major components that form the product also have unique IDs (and many are both human and machine-readable with dot-matrix, bar or QR code etching), but many of the parts are referenced at an *Entity_Type* level and contain no part information or unique identifier.

The finished product is sensorised measuring key parameters including torque, speed, temperatures, and pressures, all linked to the engine control unit (ECU). Slave sensors are also fitted for engine performance testing but are not available in MoL. The on-product sensors that exist when it enters MoL are designed to feed PID controllers for optimising performance.

At the remanufacturing facility human and material resources, BoM and WIP is managed by the cloud ERP system QAD Next Generation, whilst equipment resources, capability, and capacity planning along with process design is managed by the manufacturing engineering team using Excel spreadsheets. The process itself remains highly-manual, with discrete workstations that are managed at a shop-floor level. There is little to no use of simulation tools to plan the remanufacturing process and no system to provide visibility of inbound core quality, failure mode or automated decision making on what could be salvaged at unit level.

The *Virtual_Entity* is utilised in the *Entity_Simulation*. In this fabricated scenario, fleet data suggests engines in similar environments all suffer from valve failure. With this information, the *Decision_Making_Module* triggers a CFD and FEA simulation to be run in *Entity_Simulation* to estimate valve guide life as per Roth (2003). In this scenario RUL and EoL are estimated to be $3x10^9$ cycles and June 2030 respectively with a current quality (*eQuality*) of 70%. The failure (*eFailure_Mode*) assessed by the *Entity_Simulation* indicates valve or guide wear as the leading mode, with an EoL confidence (*EoL_Confidence*) level of 65%. *EoL_Confidence* is a function of time of latest data update, accuracy of readings, the similarities between this asset and others in the fleet and the results of the simulations. The *Available_Core* would list all potentially remanufacturable components from this engine should the failure mode be realised. Those components would then be used to populate the virtual core (*Virtual_Core*) for remanufacturing process simulation.

4.6 Discussion

Using the above case study and engine failure scenario, an assessment of the proposed model can be made. Several gaps can be identified. Currently, many parts that constitute the product do not possess unique IDs. The product itself does not have an online presence. It does not have GPS or a clock for *Entity_Time_Location* data. *Field_Activity* and *In_MoL_Mod_Entity*

data cannot be digitally populated currently (although service systems do exist). The CAD models that are available represent only the family, not the individual product. The sensors that are fitted are there for performance optimisation, not fault detection, and design *(As_Designed_Entity)* and production *(As_Built_Entity)* information exists but it is decentralised and inaccessible remotely. Some of the remanufacturing planning is done on an integrated cloud-based ERP, but much of it remains on human-driven Excel spreadsheets. Whist effective, it lacks integration and autonomy. It is possible to extract a unique virtual ID from the real product ID but beyond that the extraction of the *Virtual_Core* from the *Virtual_Entity*, the relationships it has with the information from the *eFuture_State*, *Process_Simulation*, *Reman_Opportunities* and the *Decision_Making_Module* need to be further defined and explored.

4.7 Conclusion

Cyber Physical Systems, Asset Administrative Shells and digital twins are emerging from the Industry 4.0 paradigm, competing, and often overlapping in the same development space. In this work, the digital twin (DT) has been proposed as the tool to improve and automate decision-making for remanufacturing, improving visibility of inbound core quantity, quality, demand, and processing opportunities. Although the DT concept appears less mature than the other two, greater emphasis is placed on its simulation capabilities which is a significant attribute when predicting life expectancy, failure modes, and processing outcomes for remanufacturing cores.

Both remanufacturing and DTs are growing in popularity among researchers. Despite this, there are significant gaps in the definition and development of the DT and its implementation in the remanufacturing industry. This work offers a first step towards filling these gaps by first clarifying the remanufacturing issues, translating them into DT requirements, creating a universal DT model and evaluating the model using a case study. The main challenge to DTs

being utilised for remanufacturing purposes is access to BoL and MoL data. Intellectual property rights as well as MoL data privacy and security are a sensitive subject and are unlikely to be resolved with current technologies and systems in many applications (e.g., military).

A limitation of this work is that it utilises only one case study to evaluate the model. Whilst it offers a useful insight into one business that has a strong and celebrated remanufacturing presence in the UK, it should not be deemed representative of the entire sector. There are several potential future work streams including assessing the model for other existing or prospective remanufacturing businesses including independent remanufacturers and looking at how the lessons learned can be translated to other sectors. However, the main gaps relate to the metadata that needs to be derived, and how the individual business systems that currently manage the entire product lifecycle are coupled closer together to enable a product DT that supports remanufacturing.

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4.9 Published Material Notes and Linking Section

The following information should help the reader understand the link between Chapters 2 and 3 and expands on material that was not published, but deemed relevant, by the author or examiners.

4.9.1 Notes

Section 4.5.1 discusses the case study used in this work. To expand on the parameters used and what is currently available on the product, could be made available, or would need to be constructed are summarised in Table 4-2.

Table 4-2 Parameters used in Figure 4-6 and Figure 4-7

Class	Parameter	Real and known / available on current product	Real and could be made available on current product	Would need to be constructed
eFuture_State	eRUL			X
	eRUL_Units			X
	eEoL			X
	eQuality			X
	eFailure_Mode			X
	EoL_Confidence			X
	Available_Core			X
Field_Activity	Action_ID			X
	Action_Init.			X
	Action_Desc.			X
In_MoL_Mod_Entity	DMM._Init._Activity			X
	Mod_Date			X
	Mod_Desc.			X
	Auto_Release			X
	Field_Init._Activity			X

Entity_Time_Location	UTC		X	
	Latitude		X	
	Longitude		X	
	Altitude		X	
As_Designed_Entity	Entity_Type	X		
	CAD	X		
	BoM	X		
	Manual	X		
	Test_Spec.	X		
	Test_Interfaces	X		
	FLOPS	X		
	MSDS	X		
	Software_Spec.	X		
	Operating_Limits	X		
	Compatible_Parent_ID_Type	X		
Real_ID	ID	X		
	ID_Type	X		
Current_Status	Incarnations			X
	Status			X
	Available			X
Entity_Simulation	Sim._ID			X
	Sim._Parameters			X
	Sim._Results			X
Virtual_Entity	Last_Update			X
	Parent_ID			X
	Child_of_Parent_Since			X
Virtual_ID	ID			X
	Last_Update			X
Entity_Group	Group_ID	X		

Sensor	Sensor_ID	X		
	Sensor_Type	X		
	Meas._Desc.	X		
	Sensor_Units	X		
	Meas._Accuracy	X		
Sensor_Data	Meas._Timestamp	X		
	Sensor_Value	X		
As_Built_Entity	Critical_Char._Results	X		
	Special_Char._Results	X		
	Test_Results	X		
	Firmware	X		
	Approved_Deviations		X	
Real_Entity	Release_Date	X		
	Parent_ID	X		
	Child_of_Parent_Since	X		
Virtual_Core	Last_Update			X
	Parent_ID			X
	Child_of_Parent_Since			X
	memberName			X
Process_Simulation	Sim.ID			X
	Sim._Parameters			X
	Sim._Results			X
Reman_Opportunity	Complete_Reman			X
	Partial_Reman			X
	Hybrid_Reman			X

The use cases allowed the system to be designed and its documentation allows others to build alternative solutions to the one that is progressed in Chapter 5.

4.9.2 Linking Section

Chapter 5 looks to resolve some of the requirements defined in Chapters 2 and 3, building on the design proposed in Chapter 4 from a practical perspective.

5 EXPERIMENTING WITH DIGITAL TWINS FOR REMANUFACTURING

Chapter 4 discusses the extraction of the DT requirements from the remanufacturing uncertainties. However, not all requirements derive from uncertainties. Listed below in Table 5-1 are those that have been identified in Chapters 2 and 2.9, that are not included in Chapter 4.

Table 5-1 Extended DT reqiurements to enable smarter remanufacturing

ID	Requirement
u	A human-machine interface with remote, secure connection will be needed to enable updates and observations through life
v	Longevity of the DT platform will need to be considered as entities can exist in circulation for decades
w	The platform will need to be established with the OEM. The OEM may have to host it for the entities entire life cycle or enable its transfer. This impacts IP, ownership, and DT upkeep
x	An appreciation that not all remanufacturers will be able to choose whether a product is manufactured or not due to contractual obligations, and what is deemed to be valuable will vary between stakeholders (Charnley *et al.*, 2019)
y	Environmental impact and multiple "simultaneous" failure mode modelling are challenging
z	Much of the knowledge that exists in remanufacturing does so in the workforce. Knowledge transfer, and how subjective information is handled, may be beyond the scope of this work

Having amalgamated all sets of requirements for ease of reference (Table 5-2), this chapter will document the development of a system utilising Industry 4.0 technologies (as per Dalenogare *et al.* (2018)) that incorporates a high-value entity simulator and associated digital twin prototype (HiVES-DTP) to explore data-driven decision-making in remanufacturing whist demonstrating IoT technology. The reason for developing the HiVES-DTP is to help answer the question, how are the product DT requirements realised at an operational level when using real-world systems and data?

DT enabling tools do exist, but as they are built on different formats, protocols and standards their integration is cumbersome (Qi *et al.*, 2019). According to Chen and Huang (2021) there exist difficulties with current theories and applications with respect to the practical implementation of digital twins in remanufacturing supply chains that can be further explored. Additionally, a higher technology readiness level is required of IoT technology for applications in industrial settings (Tolio *et al.*, 2017). Efforts should then be devoted to integrating and demonstrating existing solutions on a pre-industrial scale, in order to support businesses transition (Tolio *et al.*, 2017). As a result, this work looks to answer a further question. Can existing platforms and off-the-shelf components be used for laboratory based IoT experiments and if so, how?

Table 5-2 Product DT specific requirements to enable smarter remanufacturing

ID	Requirement
a	The visibility of MoL status and performance
b	An estimate of remaining useful life
c	An entity quality metric
g	Access to the original CAD models and BoM
h	Visibility of the as-built in-process verification results
i	Access to the latest BoM containing component material level data
j	Location and readiness of the of entity when it reaches EoL
k	Unique identification of entities
l	Uniquely identify remanufacturable components within an entity
m	Enable the “remanufacturing” of the digital entity
n	Access the entities original as-shipped performance results
u	A human-machine interface with remote, secure connection to enable updates and observations through life
v	Longevity of the DT platform

The composition of complex systems containing DTs will be used as a framework to answer the questions posed. As adapted from Tao *et al.* (2018) it is as follows:

$$DT = f(PE, VE, CN, DD, Ss) \tag{5.1}$$

where PE is the physical (real) entity, VE is the virtual entity, Ss stands for services for the PE and the VE such as host and simulation environments, DD refers to DT data, and CN are the connections between PE, VE, Ss and DD. These functions will be used as category headings in the remainder of this chapter with section 5.1 describing the physical entity simulator, 5.2 the virtual entity, and 5.3 the connections and data. The services are discussed separately in greater detail in section 5.4.

5.1 The Physical (Real) Entity Simulator

MoL data is critical to the DT but it was not available for the land-based engine product discussed in section 4.5. As a result, it was necessary to look for publicly available whole life performance information for a similar kind of HiVE. NASA Prognostics Center of Excellence (Lau, 2017) would provide this. Set up as an umbrella group for prognostic technology development it has a data repository that is used by the research community. Unfortunately, the performance datasets available were for aeronautical not land based installations, so it was necessary to build a new case study using an aircraft engine as the subject. However, as land and aero engines measure similar parameters, the high-value engine theme was maintained, and lessons learned may be transferable. The Rolls Royce Trent 500 engine (Figure 5-1) was used as a base case study as some production data was publicly available and the performance dataset parameters loosely matched those expected from this entity.

Without access to an aircraft engine to explore the DT concept, one needed to be simulated. The HiVES represented the real physical part of the DT and it needed to consist of at least one measurement device, be networkable and able to transmit data as a minimum (section 4.4.1).

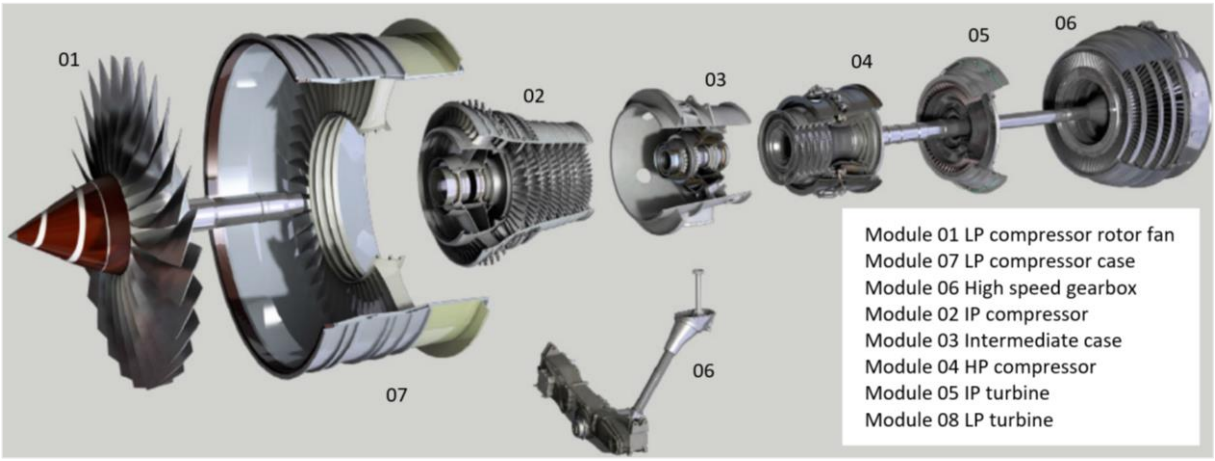

Figure 5-1 Trent 500 (adapted from Rolls Royce Plc (2014) and Gunston (1989))

Limited to low-cost electronics the real-time data, demands were met using three sensors connected to a small, cost-effective single board computer (the Raspberry Pi (RasPi) Zero W) that can be integrated and programmed to communicate over Wi-Fi (Figure 5-2).

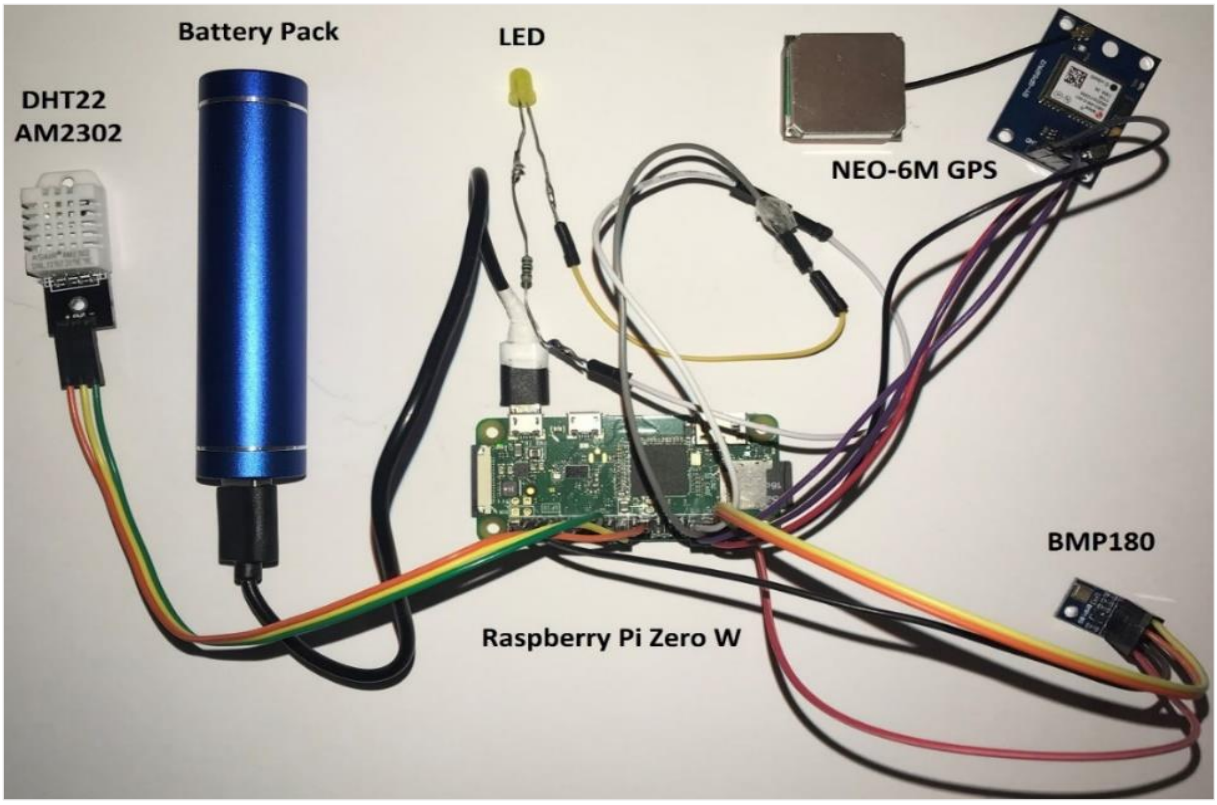

Figure 5-2 HiVE simulator set-up

The level to which a product needs to be intelligent depends on stakeholder requirements. Components that make up the entities do not necessarily need to be intelligent. Similarly, a collection of intelligent components does not necessarily form a 'smart' product. However, a key attribute that makes products 'smart', is awareness of their host environment. Land based engine performance results are expressed with respect to standard conditions (International Organization for Standardization, 2016) which requires measurement of local temperature, humidity, pressure and altitude. Aviation engine performance metrics require similar (European Aviation Safety Agency, 2007) to correct for differing host environments. For the simulation, a DHT22 AM2302 will measure local ambient temperature and humidity, whilst the BMP180 will measure barometric pressure. This will demonstrate connectivity to the IoT

and the capturing of sensor data using both hard and soft real-time links. The basic wiring arrangement is shown in Figure 5-3.

The DT should reflect the location of the real entity. As low-cost global positioning systems (GPS) are readily available, the location of the RaspPi will be tracked using a NEO-6M GPS Module with EEPROM and Built-in Active Antenna APM2.5 APM2.0 l as if it were the real entity. This module demonstrates another level of IoT complexity as the GPS connects directly to the satellite network. A Python3 script pushes the satellite data to PubNub, a publish/subscribe messaging API to demonstrate this soft real-time emerging capability. To close the loop, the ability to not only monitor, but to also control the HiVE remotely as an output of the DTP, is tested using a simple LED set to ON/OFF.

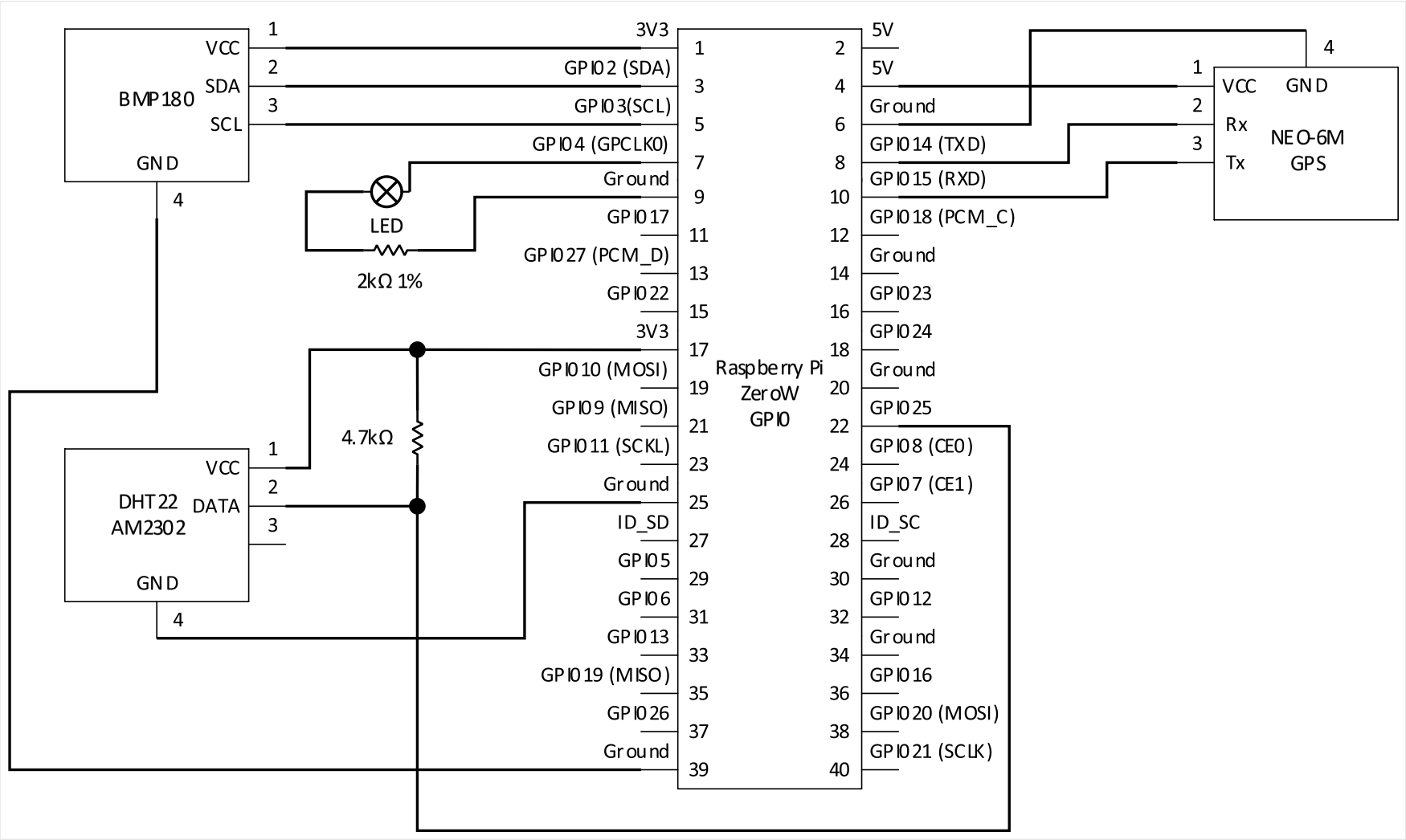

Figure 5-3 Simulator wiring RaspPi GPI0 to BMP180, DHT22 and NEO-8M GPS sensors

5.2 The Virtual Entity

In an optimal solution the virtual entity is expected to be accurate "*from a micro-atomic level to the macro-geometrical level*" (Grieves and Vickers, 2017) and information obtained through inspecting the physical entity could equally be retrieved from its DT. The unique identification of entities in the real world can be achieved by generating part numbers and labelling (requirement ID l). This can be reflected in the virtual world as a CAD models with *Virtual_ID* (requirement ID k) but that is about as far as it can go. With the technology available at this time (along with the fact that the HiVE is simulated), micro and macro level accuracy is unobtainable and medium fidelity is more likely. Every aspect of the physical twin will not be captured in the virtual one. Twining is the act of synchronising the virtual and physical states of the entity and, or environment and twining rate is its frequency of occurrence (Jones *et al.*, 2020). A balanced approach to the depth of twinning and the twinning rate is needed to keep the experimental system stable enough to perform (speed, processing, and data handling limitations) but also to synchronise parameters at a frequency that demonstrates the concept of the DT. Limited by the processing power of the RaspPi, the DTP will be updated at least every 120 seconds.

As described in section 4.4.3, some information can be made available in BoL DT instances. The 'as designed' instance can provide access to the original CAD models and BoM (requirement ID g), and the 'as manufactured' instance can provide the unique identification of entities, visibility of the as-built in-process verification results and access the entities original as-shipped performance results (requirement ID k, h and n respectively). It appears logical for OEMs who intend to manage their own products at EoL to host this information on existing PLM or ERP platforms, such as Siemens TeamCenter (Lejon and Jeppsson, 2015), but if

remanufacturing is to be outsourced, or for 3rd party remanufacturers, an alternative accessible solution is needed.

There have been proposals for EoL decision-making that depends primarily on entity RFID tags to store this information (Wan and Krishna Gonnuru, 2013, Ondemir and Gupta, 2014, Zhang *et al.*, 2017, Nowakowski, 2018) but practical limitations exist (Nowakowski, 2018). However, considering RFID tags as facilitators to address or direct systems to the information that is stored elsewhere (Kiritsis, 2011, Musa *et al.*, 2014, Li *et al.*, 2015, Yi and Park, 2015, ElMaraghy and ElMaraghy, 2016, Gu *et al.*, 2017, Tornese *et al.*, 2018, Zhang *et al.*, 2018, Ullah and Sarkar, 2020) appears to be a more practicable solution, with cloud facilities being a popular depository for large, unfrequented data (Mourtzis, Doukas and Bernidaki, 2014, Wang *et al.*, 2014, Romero and Vernadat, 2016, Tao *et al.*, 2016, Fisher *et al.*, 2018, Wang, Ong and Nee, 2018), like those containing the BoL instances required for the DT. With this information IBM's Cloud Object Storage (COS) service is chosen for the HiVES-DTP instance as it provides readily available, free to use (limited) secure, unstructured storage where data is encrypted in transit and at rest, and accessed over HTTP using a REST API (IBM, 2020). The node-red-contrib-cos (Hahn, 2020) node set offers editable deposit, retrieve and management of objects from the COS. Four COS buckets will be established, one for each instance defined in section 4.4.3 ('as designed', 'as manufactured' 'current state' and 'future state'). The node-red-contrib-cos functionality will be embedded into the virtual entity's user interface to enable the remanufacturing of the digital entity (requirement ID m) in the current state bucket only. Simplified BoM and CAD files will be used as examples (see section 5.4.4 for more detail).

5.3 Connections and Data

Connectivity between the physical-virtual and virtual-physical entities and environments (Figure 5-4) will be achieved in several different ways. The Raspberry Pi Zero W has 802.11 b/g/n wireless LAN and Bluetooth 4.1 connectivity capabilities (Raspberry Pi (Trading) Limited, 2020). Node-red, an open-source JavaScript visual programming platform built on Node.JS developed originally by IBM for integrating hardware, Application Programming Interfaces (APIs) and online services for IoT (Lewis, 2016) is used on the RaspPi to manage many different information flows.

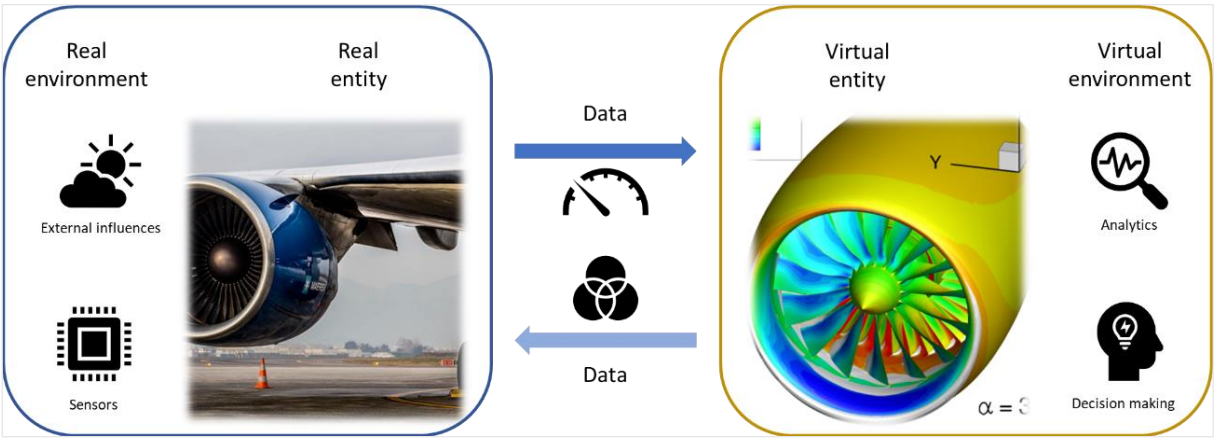

Figure 5-4 Schematic of DT elements

In this experiment Node-red will be used to simulate the engine and electronic control unit (ECU) outputs, push, pull and modify data packets. A selection of the flows in Node-red is in Figure 5-5.

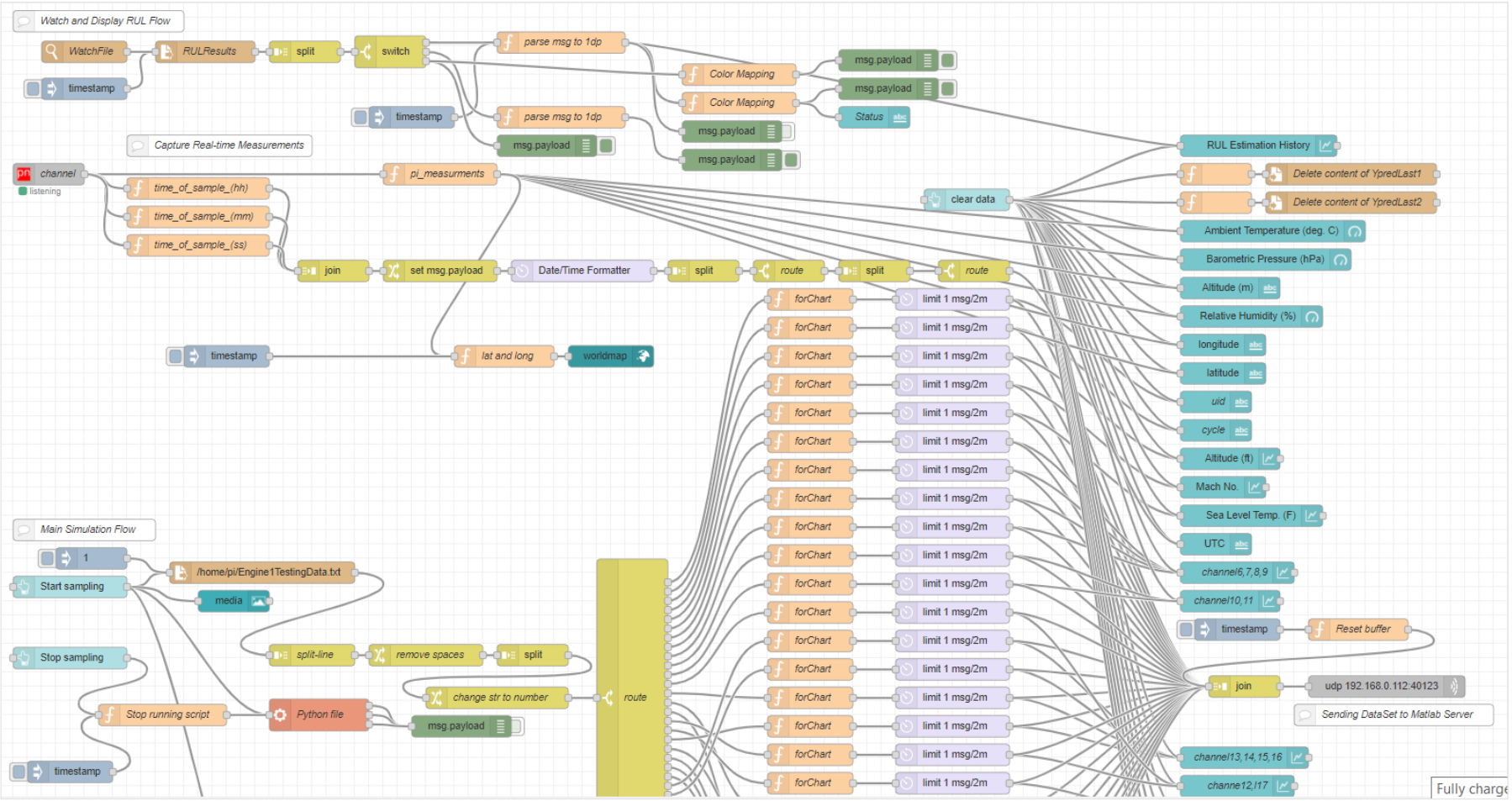

Figure 5-5 Node-red environment displaying part of the HiVES and DTP

To progress this concept, real-time and historic data need to be fused. Real-time sensor data is generated using shop-bought components, but whole-life information was needed to plug the MoL data gap. The NASA Prognostics Data Repository provides time-series data primarily for the development of forecasting systems. The chosen dataset (Saxena and Goebel, 2008) comes from a simulated turbofan engine. At the beginning of the dataset, the engine is operating normally but as time goes on the data characterises degradation or failure in different operating conditions.

For this work, the NASA PCoE turbofan engine dataset has been reduced to one engine per file so that it is small enough to be loaded on, and handled by, the RaspPi. The new dataset is injected into Node-red once 'Start Sampling' on the UI has been clicked. At the same time, the Python3 script is enabled and Node-red subscribes to the PubNub API. Node-red parses the data at intervals then rebuilds it to form packets that represent a single snapshot of engine performance containing 24 different parameters (listed in Appendix C). The packets are sent to a second instance of Node-red running on a Dell Inspiron 7591 acting as a server using UDP (Figure 5-6). UDP has been selected over TCP as it is a connectionless protocol, and the data is not critical. Packets are likely to get lost due to internet connectivity issues during MoL operation, so a connectionless protocol is more desirable.

The Node-red instance running on the server listens for the UDP packet on a pre-defined port. On receipt it triggers a Matlab script (Appendix C) to run. The latest UDP delivered packet contains the testing data. The outputs of the script are the services described in the next section.

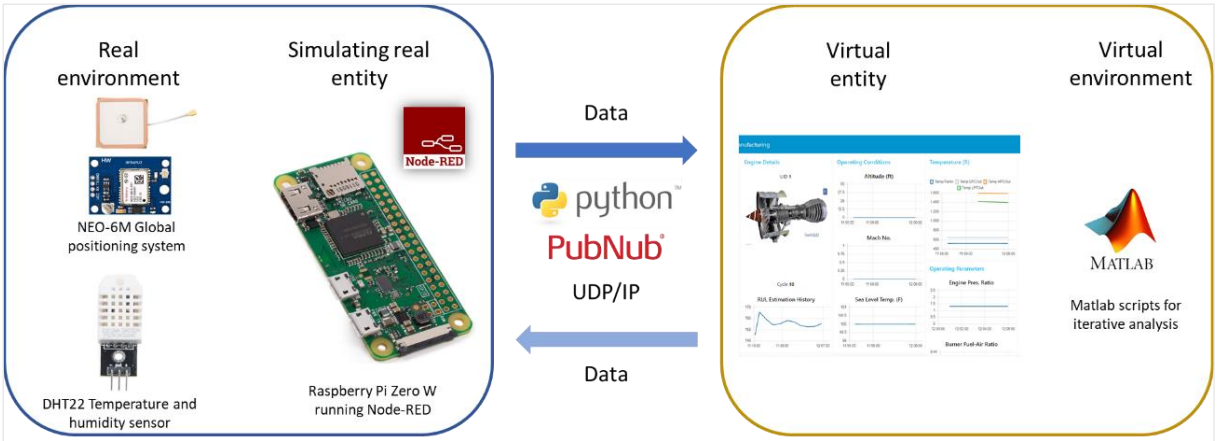

Figure 5-6 Schematic of simulation and virtual twin

5.4 Services

The services are referred to as 'virtual processes' in Jones *et al.* (2020), and include simulations, modelling, optimisation, health monitoring, diagnostics and prediction activities. These services are designed to facilitate insight and make predictions on outcomes given specific inputs. However, the service element of the DT concept is still not well defined. The size and scale transcends from non-existent to completely dependent (Negri, Fumagalli and Macchi, 2017) in published state-of-the-art. Services take place within the product specific class elements *Virtual_Entity*, *Entity_Simulation*, *eFuture_State* and *Virtual_Core* that interface with the process class elements *Reman_Opportunity*, *Process_Simulation* and the *Decision_Making_Module* from section 4.4.4. It is in the product specific class elements where many of the product-based requirements for the DT will be met. These include requirement ID's a-c, i, and j. These five requirements will title the sections 5.4.1-5.4.5 as the development of the DTP is documented further.

5.4.1 The Visibility of MoL Status and Performance

The node-red-contrib-ibm-watson-iot (GitHub, 2018) node set was originally used to connect to a Graphical User Interface (GUI) built on the IBM Cloud. The premiss being that once inside

IBM Cloud (initially IBM Bluemix until it was phased out early 2018) the project could utilise IBM's AI service IBM Watson. However, the regular service outages when Bluemix was changing to Cloud, and the need to modify connections, stop and re-start services, the lack of obvious uses for the AI in the emerging scope, and in parallel the advancement of the node-red-dashboard, inspired a move to the Node-red solution that could be hosted locally. This period of change highlighted the issue of accessing on demand and storing, frequently changing data on a global cloud platform over an extended period. Interestingly, as recently as 2019, IBM opened Watson up to interface with other cloud systems having recognised that real business data is often distributed in many places, and there was a need to accommodate hybrid, instead of single source solutions (Lardinois, 2019). As proposed in this work, frequently changing data will be manged locally, with the legacy (early life instance) data stored on the IBM Cloud, representing a hybrid-style system.

A Node-red GUI (OpenJS Foundation, 2019) will enable the visualisation of the virtual entity (requirement ID u). Split across 4 tabs found on the left of the page, 'Live Status', 'Engine1', 'EoL Fwd Planning' and 'Owner Interface', sensor readings, information and data will be presented and interactable (where necessary) on a dashboard accessible locally on the url host:1800/ui (Figure 5-7).

The MoL status will be shown as 'good', 'caution' or 'failed' evaluated as a function of RUL (see section 5.4.2 for details) whilst performance measurements per cycle will be charted (Figure 5-8).

Figure 5-7 EoL Fwd Planning tab showing cloud interface, MoL status and RUL

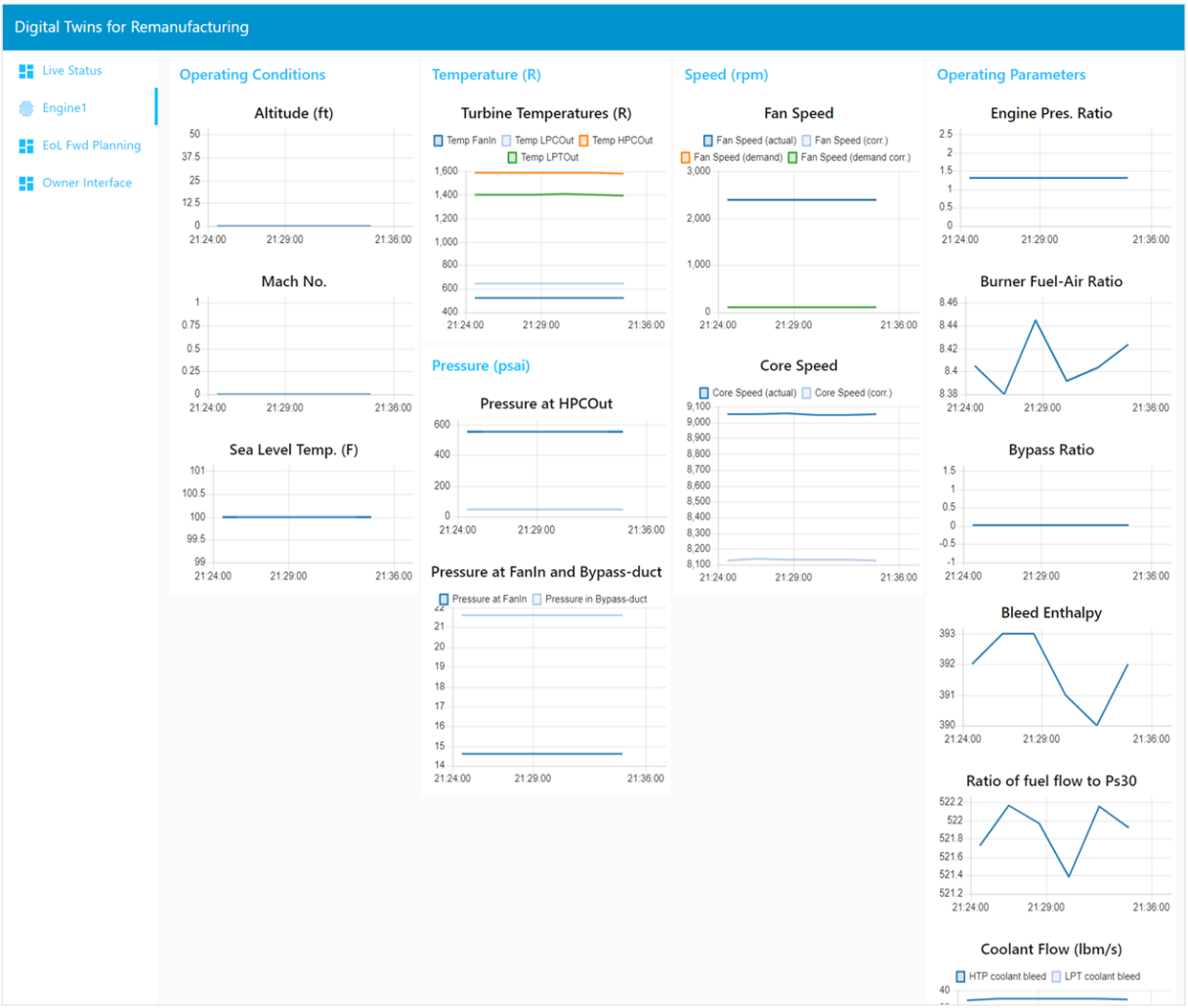

Figure 5-8 Engine1 tab displaying performance (sensor) data from cycle 1-6

The Node-red code running on the RaspPi for both the client and server are found in Appendix A and B respectively. The Matlab code that runs the RUL evaluation can be found in Appendix C. This script is a modified MathWorks (2020) sequence-to-sequence regression using deep learning example code. It imports a deep neural network that has already been trained. It has been trained using a long short-term memory (LSTM) network and the Saxena and Goebel (2008) test_FD001.txt dataset. The python3 code used to manage the sensors and trigger the Matlab script is in Appendix D. Once 'Start Sampling' has been clicked the HiVES starts to act as a real entity and the DTP begins to reflect the real entity in the virtual world.

5.4.2 Remaining Useful Life

RUL has been identified as a key requirement of the DT and its prediction would be a useful service for remanufacturing. Yet the complexity of the relationships between monitoring systems and RUL means that there is no 'best method' for estimating it (Si *et al.*, 2011).

RUL estimates can be model or data-driven based (Medjaher, Tobon-Mejia and Zerhouni, 2012) or a hybrid of the two (Zhao *et al.*, 2017). Model based estimates can be useful when existing data is limited but failure propagation processes are complex and authentic physics-based models are difficult to generate (Tian, 2012). The integration of subjective expert input has been proposed as a solution but few researchers consider the effect of this knowledge or how it may be integrated into the model (Si *et al.*, 2011). Alternatively, data-driven models use direct or indirect monitoring to provide input (Tian, 2012) which better suits this application. As identified in the case study (section 4.5), indirect measurements are more likely in HiVE scenarios. Assessment will rely on performance variables collected at discrete points, combined to represent entity health, as single indicators are rare. In this regard, the mapping of relationships between sensor data and entity degradation to form a monotonic measurement, continues to be a popular research topic (Si *et al.*, 2011). Tian (2009) offers a single variable,

‘life percentage’, based on current age and RUL. Exploring this relationship and associations including entity health, quality, failure, and reliability is needed to generate the detailed code for the DT services to make them useful to remanufacturing.

The estimate of RUL (e_{RUL}) is a variable that has a probability distribution. It is a function of external conditions, not just time, and there exists uncertainties in prognostics and interpretation. Estimating the uncertainty using propagation of error techniques is a non-trivial problem that involves calculating the probability density or cumulative distribution function, yet it is rarely possible to do so accurately (Sankararaman and Goebel, 2013). Sankararaman (2015) explores this in depth and suggests distribution types should not be assigned to the e_{RUL}, that the profile may change throughout MoL operation, and that there is a chance that multiple modes may exist. They suggest that the different sources of uncertainty should be propagated independently to form an accurate probability distribution but, in this experiment, the complete list of uncertainties are unknown, and this level of detail would distract from the aim. So, whilst it is recognised that a probability distribution of a complex system is likely to be non-linear, it is assumed, for this experiment, that all uncertainties follow a normal distribution as in Huitian, Kolarik and Lu (2001) and Hu *et al.* (2014). Figure 5-9 shows an e_{RUL} and failure probability based on the above assumption.

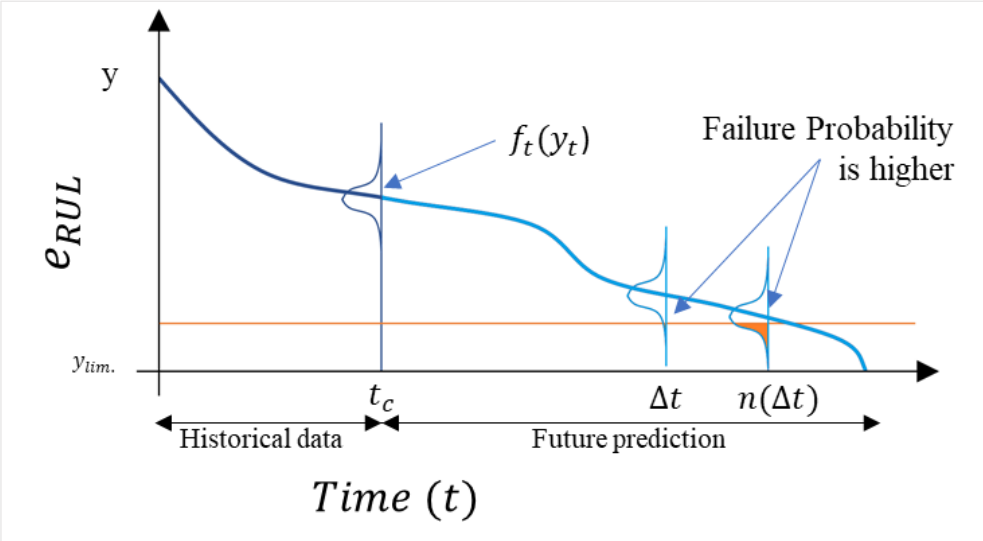

Figure 5-9 RUL estimation and failure probability (adapted from Hu et al. (2014))

If e_{RUL} decreases with time, and $y_{lim.}$ is a safety limit set to minimise the risk of catastrophic damage, failure can be defined as when y_t falls below $y_{lim.}$ (coloured orange).

If y_t has a normal distribution, the failure probability of the entity at time $t + l\Delta t$ is

$$F(t + l\Delta t|t) = e_{RUL} - 3\sigma < Y_{lim.} = \int_0^{y_{lim.}} f(y_t(t + l\Delta t)|t)dy \tag{5.2}$$

if $Y(l)$ is the predicted e_{RUL} variable at $t + l\Delta t$.

As the MoL status and performance data, captured at intervals, will be used as inputs to the RUL calculation, the conditional reliability function (Eq.5.3) can be used to express the probability that the entity will operate without failing for a given period t_y given that it has already survived to the current time t_c (HBM Prenscia Inc., 2017).

$$\mathrm{R}(\mathrm{t_y}|\mathrm{t_c}) = \frac{\mathrm{R}(\mathrm{t_y} + \mathrm{t_c})}{\mathrm{R}(\mathrm{t_c})} \tag{5.3}$$

It is then possible to set a threshold reliability and define a remanufacturing decision scheme based on e_{RUL}, expanding the approach used by Hu *et al.* (2014). They propose a scheme that considers availability of the entity to EoL management processes but ignores the readiness of both the user and the remanufacturers. By enabling these calculations in the virtual world (triggered by the python script but carried out by Matlab in this work), and engaging the entity user and remanufacturer in MoL, inputs from all sources can be used to formulate a quality metric to bolster data-driven decision-making for remanufacturing.

5.4.3 An Entity Quality Metric

Accepting that many definitions of 'quality' exist due to the complexity and diversity of the construct (Reeves and Bednar, 1994) it is possible to formulate a metric unique to this application for remanufacturing. This idea has been recently floated by Charnley *et al.* (2019) who evaluate the impact of an entity quality metric (referred to in their work as certainty of product quality (CPQ)) on processing time through a generic high-level remanufacturing process. The term CPQ implies a quality metric exists before a confidence level is applied. This does not appear to be the case in the published work. However, this should not distract from the implementation of their definition where they offered a metric that supports the suggestion from (Goltsos, Syntetos and van der Laan, 2019), that remanufacturing planning research needs to move away from the assumption of a uniform quality of returns, to the estimation and application of a distributed range. Charnley *et al.* (2019) defined the range as 0.1 to 1.0 representing the lowest to highest CPQ respectively, effectively the inverse of Tian (2009) life percentage proposal. But neither works consider the perception of quality from the users or remanufacturers perspective. These are key factors affecting entity demand, life expectancy, core availability, remanufacturability, and ultimately profitability.

The DTP can link the customer-supplier-remanufacturer data, so it is possible for a quality metric Q to be formed using:

- Entity quality as a function of performance (Q_p)
- Perceived quality of the entity to meet expectations, directly from the user (Q_u)
- Remanufacturing quality evaluated (Q_r)

Starting with Q_p, and referencing Figure 5-10(a), if failure occurs at a quality q_f, t_c is the current time, q_c represents current quality, t_f is the failure time, and t_{end} is the end of the products existence, the RUL is $t_f - t_c$. At t_f the entity has a quality of q_f but this can continue to deteriorate to t_{end} due to external factors. But waiting until a HiVE failure occurs could be catastrophic and lead to fewer remanufacturing opportunities (reduced remanufacturability). By assuming the HiVE owner aims to optimise its utilisation before making it available, there exists a window of opportunity towards the end of the MoL to evaluate EoL options. With reference to Figure 5-10(b), if q_g denotes good quality at time t_g, it is reasonable to assume the entity can remain in-use, however, after t_g but before failure t_f, labelled 'Status: Caution' the entity should be considered for remanufacturing. At point t_f and beyond ('Status: Failed'), the entity may be better suited to recycling, but this will depend on the failure mode and recovery options available.

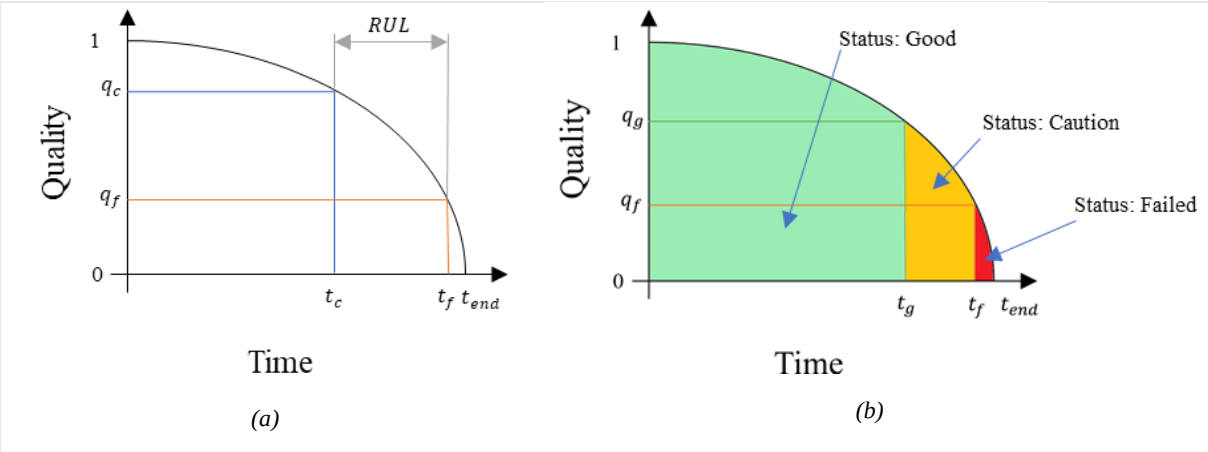

Figure 5-10 Relationship between quality (perfornance), time, (a) RUL and (b) status

The input to the remanufacturing process is used core with availability and quality dependent on the end users' willingness to give it up and usage patterns employed during MoL (Rizova, Wong and Ijomah, 2020). Regardless of whether the entity meets the performance levels set by the manufacturers or not, the user may have their own expectations (Q_u). It is possible that the entity may be 'Status: Good', but the user no longer wants / requires it. There can be many reasons for this, and the details are not important, but a facility to allow the user to initialise the EoL (or second life) evaluation is desirable and will be realised in the GUI's 'EoL Fwd Planning' tab as a toggle switch. When switched to 'ON' the details of the entity can be made visible to EoL facilitators and the *Decision_Making_Module* can be referenced.

When the entities performance has deteriorated to 'Status: Caution' the DTP can be more active in engaging the user and automatically request their approval to make the entity visible to the remanufacturer (see readiness within section 5.4.5 for more details). If the entity reaches 'Status: Failed' either via 'Status: Caution' or directly, the DTP will go straight into evaluating remanufacturing opportunities without relying on the users input. Figure 5-11 shows the status and user interactions starting with the HiVE entering service and ending when it is evaluated for remanufacturing (Q_r).

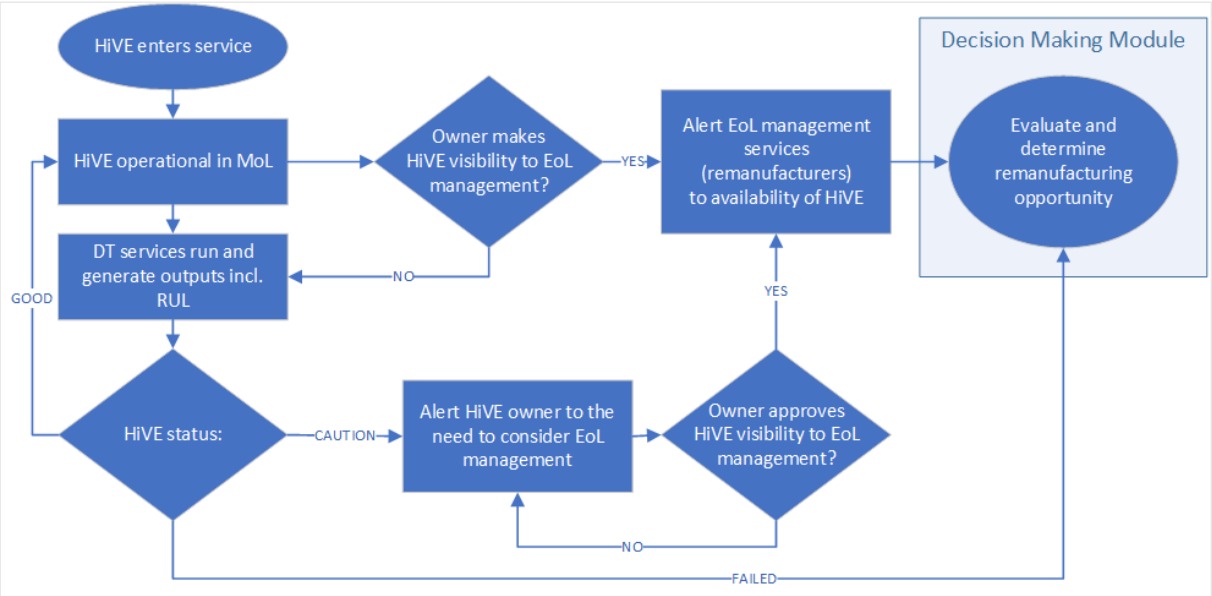

Figure 5-11 Relationship between measured, user percieved / accepted quality in MoL

5.4.4 Access to the Latest BoM Containing Component Material Level Data

Currently, this functionality relies on the diligence of the user or service provider to upload the latest BoM and CAD files to the 'current state' COS bucket. Details of what exists in the COS buckets and when it was last updated can be downloaded via the DTP 'EoL Fwd Planning' tab under 'Cloud Interface' in real-time. The vision for this was a fully integrated CAD solution where components could be automatically updated in the virtual model to reflect those in the real entity via scanning the unique ID or similar. Where component liaisons, constraints, sub-assemblies and 'correction factors' for real world dynamics were automatically understood. Where unique dimensions, material type and properties were available for analysis and simulation. Yet, whilst many of the larger CAD software providers discuss digital twins, no off-the shelf solution was found. This finding is supported by Mourtzis, Doukas and Bernidaki (2014) who are critical of the limited coverage of current CAx packages, data exchange options and interoperability, as well as the 'poverty' in adequate modelling tools for product whole life-cycle applications. The array of academic work focused on expanding existing CAx systems

for remanufacturing or disassembly planning reflect the infancy also. Many reference future studies proposed at automating the generation of the matrix-based product models from CAD files (Smith and Hung, 2015, Soh, Ong and Nee, 2015), CAD or PLM systems (Germani *et al.*, 2014), or the BoM (Luo, Peng and Gu, 2016). Cappelli *et al.* (2007) describe two methods of optimising disassembly sequences providing a foundation from which a CAD extension could be written, but do not realise it. A hybrid manual input and CAD interface using C# and SolidWorks API has been realised, but the solution is still heavily reliant on the user to specify solutions (Soh, Ong and Nee, 2016) and doesn't incorporate real world data streams.

From experience, systems like Siemens PLM TeamCenter Manufacturing Process Planner, are built such that component material level data is accessible at product level. TeamCenter does not currently interface with real data from products but Siemens MindSphere may well do (Siemens Industry Software Inc., 2020). However, for this project no such system was available, so the DTP uses dummy BoM and CAD files with .xlsx and .stp extensions (visible in Figure 5-7 under 'Cloud Interface') to prove the interaction opportunity that exist with using COS.

5.4.5 Location and Readiness of the Entity When it Reaches EoL

The GPS module described in section 5.1, provides the location of the HiVE. Latitude, longitude, altitude, and Coordinated Universal Time (UTC) are outputs from a looped Python3 script running on the RaspPi. Using UTC to timestamp the data is preferred as this avoids relying on local clocks that can be affected by intermittent power supply. Conflicting and changing time-zones are also avoided. The GPS data is presented numerically and graphically on the 'Live Status' tab of the DT user interface (circled in Figure 5-12).

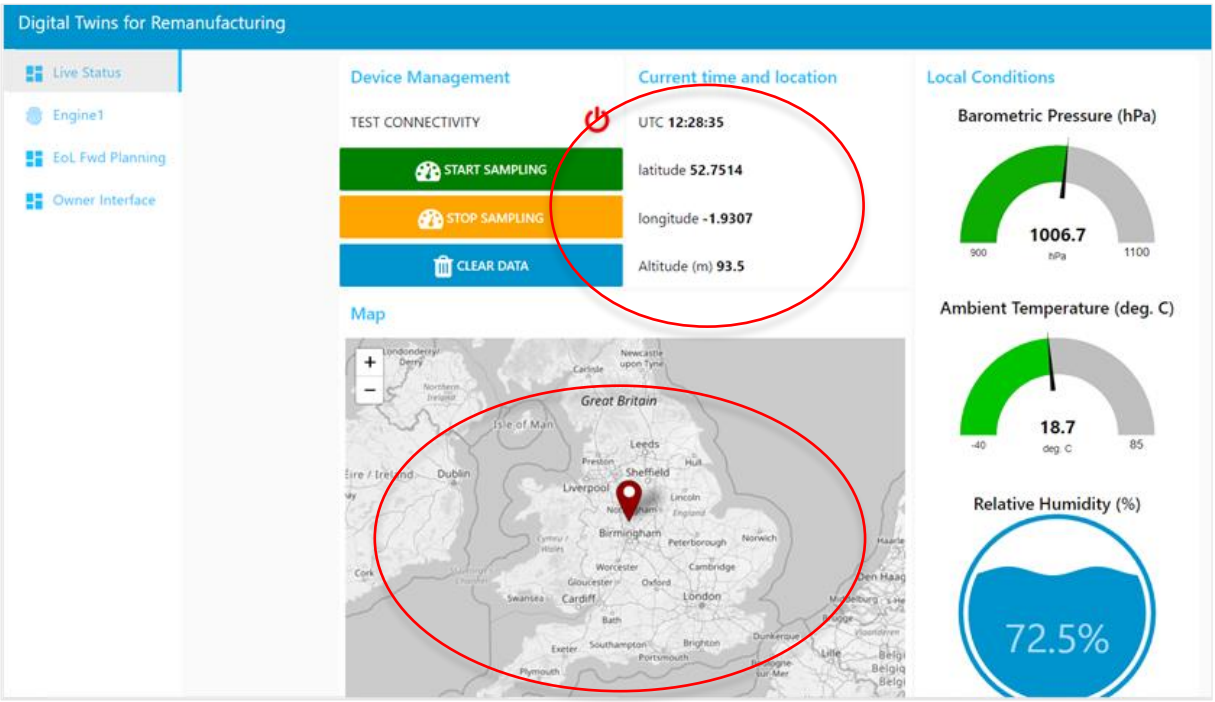

Figure 5-12 Live status tab showing realtime GPS information for the entity

The entity user can initialise the remanufacturing evaluation directly at any time through the 'USER: Enable visibility of HiVE' toggle switch in the 'User Initialised EoL Recovery' section of the 'Owner Interface' tab (Figure 5-13). However, the flow for the scenario whereby the entity remains in use until it is removed from service, is different. Assuming the DT identifies when the HiVE is best suited for remanufacturing (or other EoL management approaches) through Q_p, it is necessary to engage the end user / provider to enact recovery ($Q_u$and Q_r).

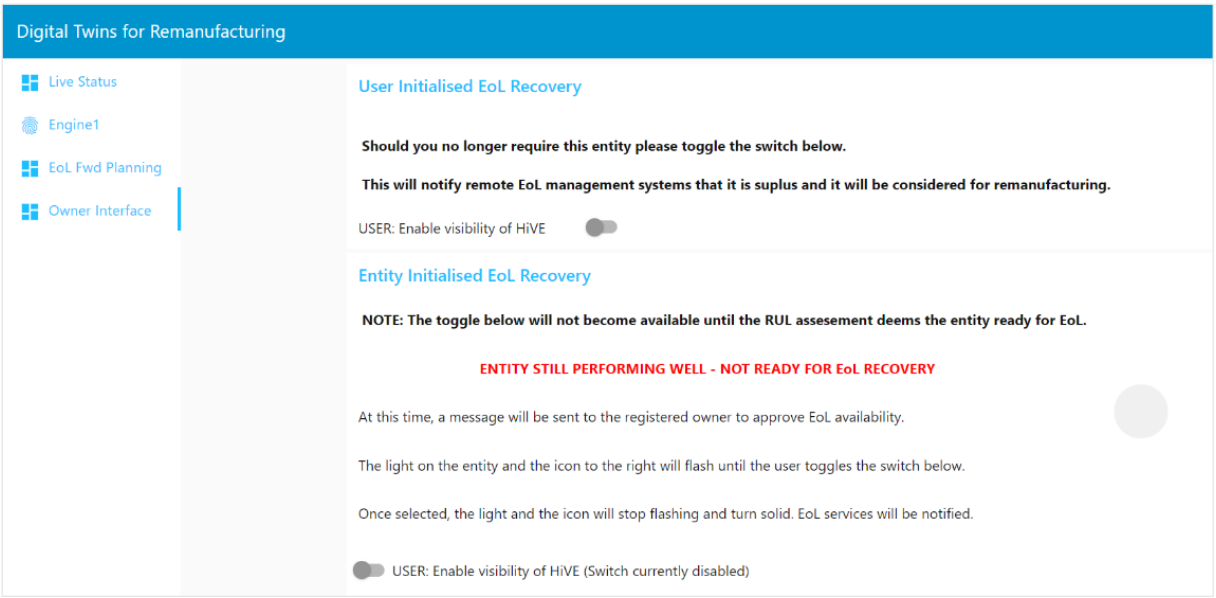

Figure 5-13 Owner Interface on the HiVE-DTP

Ultimately there are many IoT- facilitated ways to engage the end user. In this work, the system is designed to email the end-user with a link to the 'Owner Interface' tab within the DTP (Figure 5-14) that allows them to switch on visibility of the HiVE to EoL solution providers.

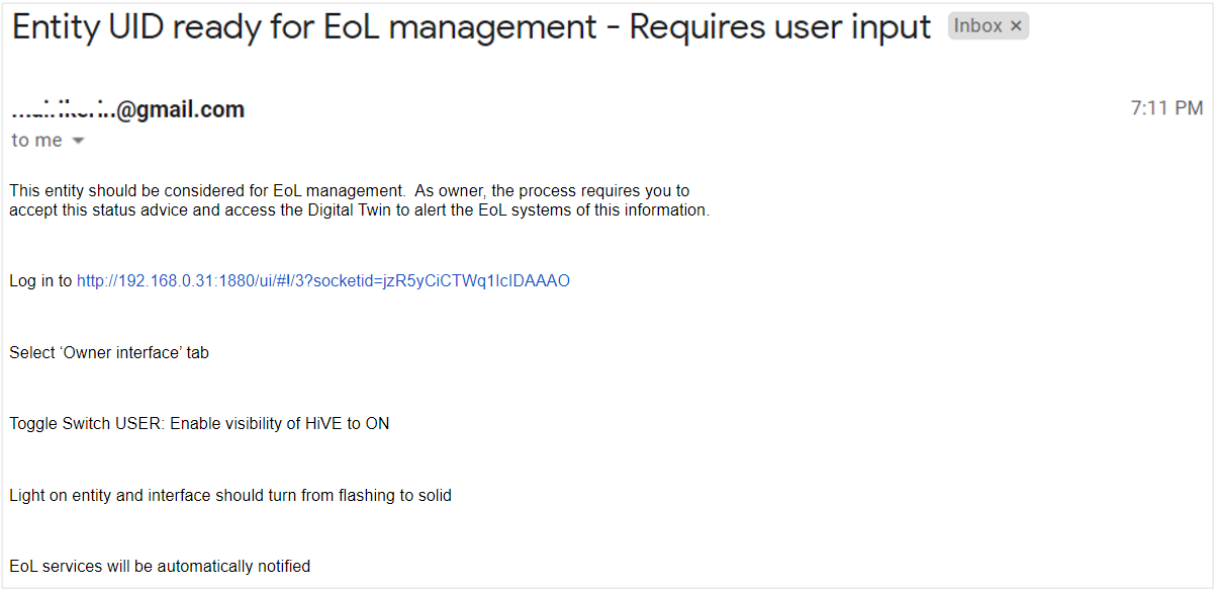

Figure 5-14 Automated EoL notification (email) requesting owner interaction

The switch is only enabled once the DT status drops from ‘good’ to ‘caution’. Once selected this can alert the remanufacturers to the readiness of both the product and the end user to recovery through similar IoT methods and trigger the evaluation of EoL options (Figure 5-15).

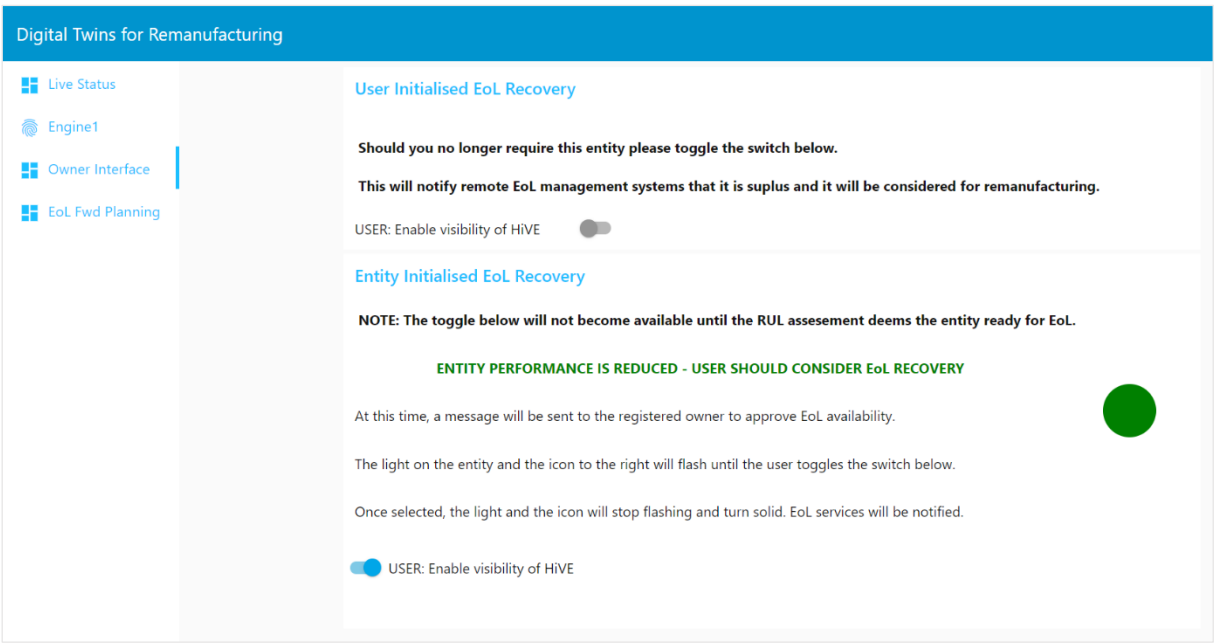

Figure 5-15 HiVE ready for EoL system consideration with entity visibility enabled

5.5 Discussion

A HiVE-DTP has been developed to support remanufacturing. It includes all but one of the elements identified in previous works. Some functions were relatively straightforward to realise whilst others were more complicated or lack maturity. Truly real-time connectivity and decision-making are still not realistic expectations using current technology and simulation approaches. (Perhaps big data analytics can reduce the dependency on simulation in the systems by avoiding them altogether or taking the activity off-line to minimise lag). However, returning answers to the questions posed at the beginning of this chapter, existing platforms and off-the-shelf components can be used for laboratory based IoT experiments for BoL to EoL product management. One example of how this can be achieved has been documented in this

chapter, but many solutions are possible as mechanical, electrical, and digital engineering becomes more integrated and the lines between the real and virtual world blur.

The proposed solution was inexpensive yet demonstrates that IoT technologies can be used to build a basic product DT. Small, single-board computers can be programmed to extract and direct sensor data, perform or instruct simulations using near real-time inputs. Cloud facilities can be used as accessible data depositories, capturing instances of the entity's life, that can both interface with the DT and be accessible to the user and remanufacturer. However, many different packages are used, and the integration is cumbersome. Additionally, whilst the system has been relatively stable for over twelve months during development, its longevity over an entity lifetime (requirement ID w) is questionable and cannot be met as part of this research. Maintaining software version alignment, structure, compatibility and licensing were all challenges experienced during the development of the prototype. This calls for greater consideration of software and data management systems for longer-life installations.

Towards the end of this research phase, Hinchy *et al.* (2020) wrote an article describing a process DT that utilises similar systems and connections to those proposed in this work. Whilst it focuses on DTs for a manufacturing process, they still control the system using a RasPi model 3B+ that wirelessly transmits sensor data via OPC-UA protocol, incorporate a product DT containing a database of features, including material properties, dimensions and condition. Reviewing their previous work (Hinchy, O'Dowd and McCarthy, 2019) it is also possible to establish that they developed a dashboard in Python for user feedback. Their service equivalent is a finite element model-based simulation used to predict the outcomes of a metal forming operation that relies on information from real sensors. The prediction output then influences the forces used in the real activity of bending. Finding this article increased confidence levels in the approaches taken in this work.

The answer to the final question in this chapter "how are the product DT requirements realised at an operational level when using real-world systems and data?" is more complicated. For each DT requirement, a real-world solution has been proposed but there were many trade-offs made along the way, particularly in dealing with the real-world data. It was difficult to decide where the different pieces of code should reside, where they should be initiated, where the decisions needed to be made and where the results needed to go. Afterall, the virtual element of the DT is all code. Defining a strategy for data management for DTs may well be a future research activity. Additionally, this DTP used one leading virtual process. This was the RUL estimation. Expanding this to include others such as FEA or CFD simulations is certainly possible but how would different results be evaluated, prioritised, and combined?

In some instances, the results from of the virtual twin services will feed back into the real twin to manage and control it behaviour to extend life expectancy. In the remanufacturing scenario the DT could be evaluated to optimise financial returns and minimise resource consumption. If all remanufacturing information is available virtually, what is preventing the emergence of a new type of business, the remanufacturing-as-a-service where the states of the cores are visible to those with access, and firms can bid for the work, and engage future users actively, using AI?

The forming of the solutions to each product DT requirement should enable better EoL decision-making but this assumption needs to be further investigated. Ultimately, the decision to remanufacture an entity, and the depth and processes used if progressed, depends on a multitude of variables (Sitcharangsie, Ijomah and Wong, 2019) not just those identified in this research. This will be looked at in Chapter 6.

5.6 Summary

This chapter has documented the evolution of solutions to the product DT requirements identified in earlier works that have the potential to contribute to improved decision-making in remanufacturing. Using a case study along with a small micro-computer, sensors, and publicly available datasets the requirements are explored. The sensors offer real-time real-world measurements that are combined with re-packaged parameters associated with product degradation. A RUL service on the virtual twin is used to predict the quality of the HiVE that in turn can modify the behaviour of the physical twin and initialise interaction with the user and EoL service provider.

6 PRODUCT DIGITAL TWIN DRIVEN DECISION-MAKING IN REMANUFACTURING

Only 6% of state-of the-art literature attempts to accommodate more than two remanufacturing uncertainties in one decision-making process (Rizova, Wong and Ijomah, 2020). Using the list of uncertainties by Rizova, Wong and Ijomah (2020), namely, 1) demand for remanufactured products, 2) returns quality, 3) returns quantity, 4) lead time, 5) returns timing and 6) routing, it has already been shown that product DTs can offer information on 2, 3, 4 and 5, whilst a process DT is likely to be able support 6. In combining the two DTs to create an end-to-end DT, all uncertainties could be contested to some degree. This highlights how significant the transformation of remanufacturing decision-making could be following the integration of DTs and the impact it could have on certainty and stability in this sector.

This chapter will build upon the lessons learned so far and explore the workings of the decision-making module (DMM). The questions that will drive this exploration include 'what are the key variables that need to be incorporated into the DMM to come to a decision' and 'if the remanufacturing business is to be managed to CE principles, how do the outputs of the DT feed into to triple-bottom line assessment and the decision as to whether an EoL product is recovered?

The chapter will be structured as follows. Section 6.1 will look at the sustainable performance metrics that could be used to make an informed decision in remanufacturing. Section 6.2 will cover the Decision-Making Module model and its structure. Sections 6.3 and 6.4 will present the results and discussions relating to the use of the DMM in a case study and section 6.5 will close out the chapter.

6.1 Sustainable Remanufacturing Performance Metrics and Decision-Making

The economic element of sustainable performance tends to be the main indicator of success in remanufacturing, however, environmental elements, particularly from OEMs who perform their own remanufacturing, are increasingly being recognised. Social factors, whilst also increasing, remain low unless consciously set up to drive positive impact (Jensen *et al.*, 2019). Specific measures of sustainable performance in remanufacturing have not been researched extensively to date and could well be subject to future exploration. Therefore, those indicators available in the public domain for manufacturing will be used as a starting point. These have been summarised by Joung *et al.* (2013) with a similar set used in a recent triple-bottom-line review into cannibalisation and remanufacturing by Okorie *et al.* (2021). Both Joung *et al.* (2013) and Okorie *et al.* (2021) discuss an extended triple-bottom line. Using their indicators it may be possible to give measurable value to key decision-making variables or calculations from existing sources.

Looking specifically at decision-making for remanufacturing Sitcharangsie, Ijomah and Wong (2019) and Rizova, Wong and Ijomah (2020) offer recent systematic reviews in this field. They focus on what factors affect the decision-making process and what types of output are generated. Their findings generally overlap. There are more similarities to difference between the elements despite them relating to performance indicators and decision-making factors, respectively suggesting a high degree of synergy.

This information helps conceptualise the whole remanufacturing decision-making landscape however, neither Sitcharangsie, Ijomah and Wong (2019) or Rizova, Wong and Ijomah (2020) probe the detail. Their work ends at a high level having reviewed the kinds of decisions made to optimise remanufacturing. The assessment and analysis methods used to make the decision and/or what a good decision looks like are not discussed. In contrast, within the

remanufacturing space, Jiang, Zhang and Sutherland (2011) do look at it in more detail and use a multi-criteria decision-making method to reach a decision, but their aim is to evaluate the best combination of equipment to invest in, not the remanufacturing process itself so whilst the concept is useful, the detail is less applicable.

There is little research that considers the DT across the entire life-cycle (Jones *et al.*, 2020) and that work focused on decision-making in remanufacturing is also limited. As far as is known, this work is the first of its kind to explore the use of product DTs in the remanufacturing process.

6.2 Decision-Making Module Model

An end-to-end DT, comprising of both the product and remanufacturing process DTs, may enable autonomous decision-making. In the DT, decision-making takes place in the DMM.

Ultimately the output of the DMM is twofold, first, a decision on whether or not a product should be recovered based on the opportunities available and, second, a set of operational principles to optimise the down-stream activities for given business objectives. In remanufacturing, these objectives are normally economics based but environmental targets are becoming more prevalent (Subramoniam *et al.*, 2013) and social elements are also emerging (Jensen *et al.*, 2019). With reference to (Figure 6-1) the DMM will need to accommodate changing business inputs (demands, limitations, and risks) and utilise the BoL and MoL data available from the DTs. The outputs are similar to those described in smart recovery decision-making (SRDM) (Meng *et al.*, 2020) and include recovery alternatives as well as product and process operational plans. Reverse logistics options are also considered in the module making use of the product and processing locations, an output that was out of scope in Meng *et al.* (2020). The ‘optimal’ solution depends on the inputs and the applied evaluation criteria.

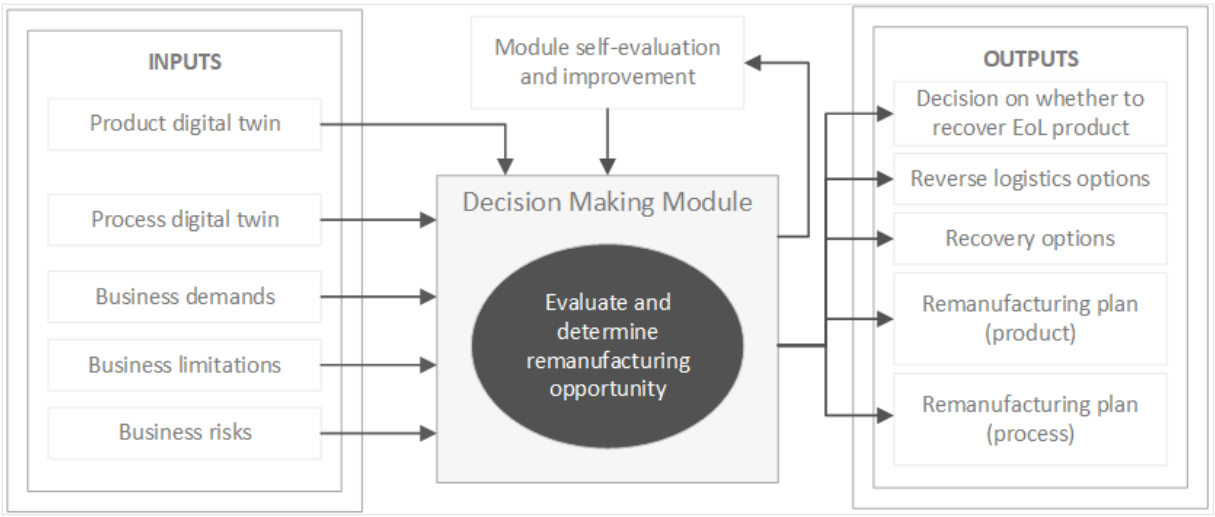

Figure 6-1 Inputs and Outputs to the Decision-Making Module

6.2.1 Module Assumptions

Product DT – This has been described in detail in Chapters 4 and 5.

Process DT – This couples the production system with its digital equivalent (Uhlemann, Lehmann and Steinhilper, 2017). It is similar to the product DT as it enables assessment and simulation of potential scenarios feeding key information into the DMM.

Business demands, limitations, and risks – Relate to the business expectations and experiences that are not captured or managed by the product or process DTs but will influence the decision.

Decision on whether to recover EoL product – This output indicates to the business the worthiness of product recovery.

Reverse Logistics Options – If the decision to recover an entity or not lies with the business, it can be data-driven. Similarly, if an entities recovery is a foregone activity (contractual etc.), options on when and where it should be recovered to can be evaluated using the DT information. The cost of the reverse logistics operation from an economic, environmental, and social perspective can be assessed using the entity GPS and remanufacturing facility locations.

Recovery Options – Relates to the choices that the remanufacturer can make to optimise bottom-line benefits once the entity has been made available. Selecting the most appropriate level of disassembly (complete, partial, targeted and, or destructive) and reassembly (complete, partial, hybrid, built-to-order, build-to-stock) is key to managing a sustainable business.

Remanufacturing plan (product) – Relates to the requirements of the existing product to start its second life via the remanufacturing process. The remanufacturing bill of materials rBoM can be estimated based on the MoL BoM, quality and performance degradation data from the DT. The remanufacturing bill of process (rBoP), much like the manufacturing BoP, defines the activities that need to happen to translate the product from one state to another, balancing triple bottom-line performance and technical competence. In this case the rBoP takes the product from EoL, back to BoL, the remanufacturing routings can be generated and may include disassembly and rebuild sequences plans, process steps, machine operations, materials, slave parts and performance targets. An accurate estimation of remanufacturing bills can benefit line balancing, scheduling and production planning (Goltsos, Syntetos and van der Laan, 2019).

Remanufacturing plan (process) – This output considers line balancing, scheduling, planning, demand management, core acquisition and inventory holding, relying heavily on the process DT, targeting the best scheme for managing tasks and demands whilst being limited by technical constraints.

Module self-evaluation and improvement – A smart decision-making module can make assessments and carry out improvements to optimise itself, but the system should allow for human intervention and preference selection. In the remanufacturing sector process planning is heavily dependent on the skills and knowledge of experienced individuals and this needs to be accommodated (He *et al.*, 2020).

Before generating the outputs, the decision whether to remanufacture or not needs to be made. This will be done by evaluating the triple-bottom-line as described in the next section.

6.2.2 Model Structure

The model (Figure 6-2) is built on a scenario where a remanufacturing business can choose whether to recover a HiVE from its MoL / EoL user.

If the costs associated with recovery and remanufacturing out-weight the business opportunities from a triple bottom-line perspective the business will not recover it (other CE practices may be applicable but these are out of scope). To make this evaluation, the business needs to identify the best remanufacturing strategy balancing profits, environmental effects, and social impact for the given HiVE location and quality from the DT, within the constraints of existing technological capabilities and management policies. Time will be used as a leading variable that will influence the economic, environmental, and social measures. It has been assumed that if a process takes longer, it will require more investment and a larger workforce, whilst generating greater environmental load. Only the benefits to the business from the point that the HiVE becomes available for remanufacturing until it is ready for its second life meeting the expectation that it will be equivalent to, or better than, the manufactured equivalent, not considering multiple life cycles, are in scope.

The model assumes that product recovery will not be triggered without product demand as the core function of this sector is to remanufacture. The decision whether to recover the product is evaluated in the DMM. Those that are recovered, are first disassembled.

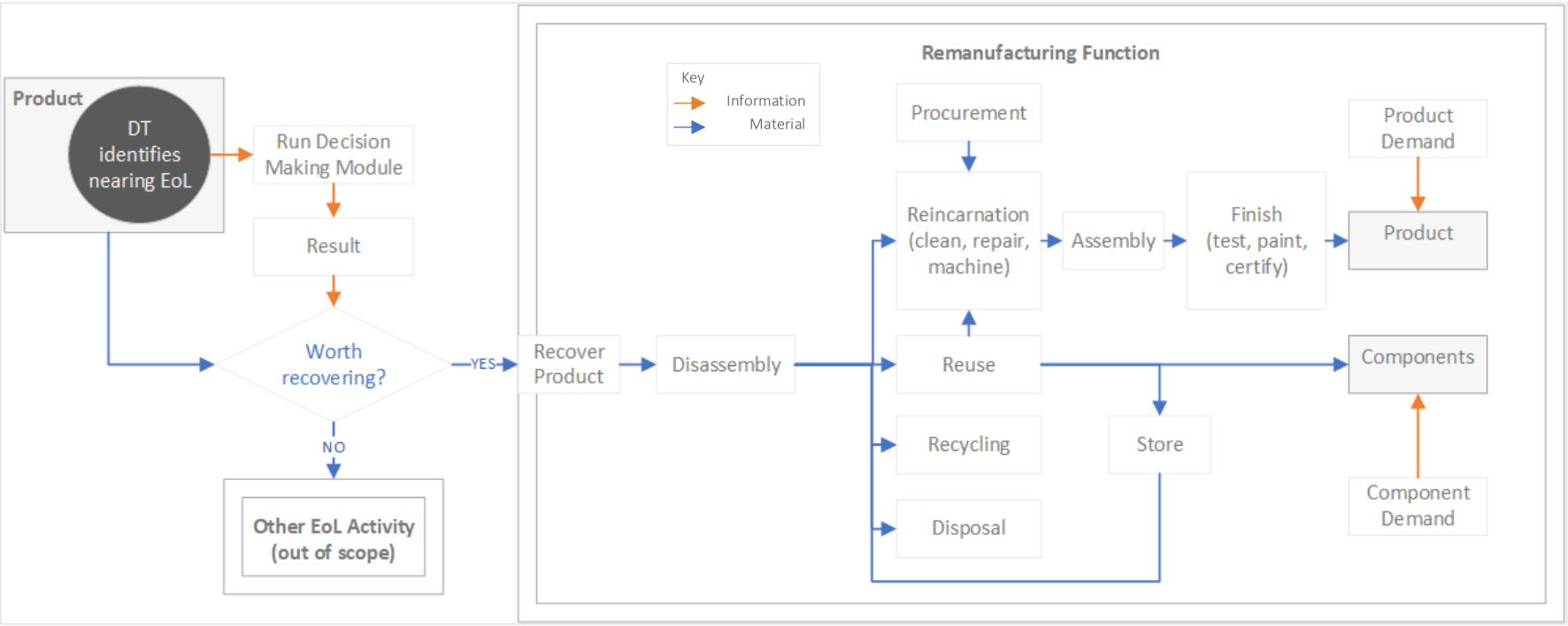

Figure 6-2 Relationships between DMM and the remanufacturing functions

Disassembly can be either complete, partial, or targeted with components progressing to a reincarnation phase (normally referred to as remanufacturing but not used in this instance to avoid confusion) that can include any combination of cleaning, repairing, machining, assembly, testing and finishing, or filtered into reuse, recycling, disposal, or storage material flows. Reincarnation has been used to describe the processes normally associated with remanufacturing as BoL assets can be made from EoL products and components.

The demand for products and/or components drives the reincarnation and reuse functions. The entire incarnation of product i may be processed through remanufacturing. However, any component j of product i that needs to be replaced due to damage, parts missing, or needing an upgrade, can be sourced from the store or component reuse. Alternatively, new components can be procured (or manufactured). Components with poor quality identified after disassembly, may be recycled, or disposed of and are lost to the system in this scenario. The routing for each approach is different.

Modifying the formulations of Ondemir and Gupta (2014) and Meng *et al.* (2017) to evaluate the options available utilising real data from the DT prior to product recovery, the economic, environmental and social impacts of remanufacturing the HiVE can be defined. A list of all variables used can be found in Table 6-1. As the economic indicators of remanufacturing are more mature, this is where the development will commence.

Table 6-1 DMM variables list

α	An action in the remanufacturing function that causes an environmental impact (shipping, disassembly, storage etc.)	ta	Time to assemble product
λ	Time functions	td	Time it takes to disassemble
ca	Cost of assembling product per unit of time	th	Time component in storage
cc	Cost of recycling component	tr	Time to reincarnate component
cd	Cost of disassembly per unit of time	tu	Time to prepare component for reuse
cdp	Cost of disposal	x	Represents reincarnation, reuse, recycling or disposal (1, 2, 3 or 4)
ch	Cost of holding component per unit of time	y	Impact categories (energy, material consumption, emissions to air and water and waste generation)
cph	Cost of preserving component for storage	B	Management of unwanted assent burden
cp	Cost of procuring component	CCA	Cost of component assembly
cr	Cost of reincarnating component per unit of time	CCC	Cost of component recycling
cru	Component revenue from reuse	CCD	Cost of component disposal
cs	Cost of shipping per km	CCR	Cost of component reincarnation
cu	Cost of preparing component for reusing per unit of time	CCS	Cost of component storage
ed	Environmental impact of disassembly of component per unit of time	CCU	Cost of component reuse
edp	Environmental impact of disposal	CPD	Cost of product disassembly
eh	Environmental impact of holding per unit of time	CPF	Cost of product finishing
ep	Environmental impact associated with the procurement of a part	CPR	Cost of product recovery
er	Environmental impact per unit of time in reincarnation	CRF	Cost of remanufacturing function
erc	Environmental benefits associated with reusing the material over virgin material	E	Environmental benefits
eru	Environmental benefits associated with reusing the component over a new component	ECA	Environmental impacts of component assembly
es	Environmental impacts of shipping	ECC	Environmental impacts of component recycling
eu	Environmental impact as a result of preparing a component for reuse	ECD	Environmental impacts of component disposal
f	Remanufacturing facility	ECP	Environmental impacts of component procurement
fr	Routes through to reincarnation from reuse	ECR	Environmental impacts of component reincarnation activities
fu	Routes through to available for sale from reuse	ECS	Environmental impacts of component storage
i	Product	ECU	Environmental impacts of reuse
j, k..z	Components	EPD	Environmental impacts of product disassembly
l	Distance in km	EPR	Environmental impacts of product recovery
m	Missing component	ERF	Environmental impact from remanufacturing function
mrc	Material revenue from recycling	ES	Environmental savings
nc	Need to recycle	H	Number of man-hours
nd	Need to disassemble component 1 or 0	J	Function representing the link between process time and man-hours
ndp	Need for disposal	Nu	Need to reuse
nh	Need to hold component	OS	Optimal solution
nr	Need to reincarnate component	SP	Sales price of the remanufactured product
nsl	Component destined for recycling or disposal	TQ1	Function representing impact of q on disassembly time
qi, qj	Product quality, component quality	TQ2	Function representing impact of q on reincarnation time
qmin	Min quality of component for use in remanufactured product	TQ3	Function representing impact of q on reuse time
ro	Routes through the remanufacturing function	TS	Function representing impact of second-life destination on disassembly time
sl	Component destined for reincarnation or reuse	WD	Weighted deviation

6.2.2.1 Evaluating the Economic Growth Impact in the DMM

In a simplified form from an economic perspective, the potential profit, P, is the sales price of the remanufactured product, SP, minus the total cost of performing the remanufacturing function, CRF (Eq. 6.1).

$$P = SP - CRF \tag{6.1}$$

With reference to Figure 6-2, the CRF includes the cost incurred by product recovery and disassembly CPR and CPD respectively, as well as component storage, CCS, reincarnation activities, CCR, reuse, CCU, recycling CCC, disposal CCD (Eq.6.2). CPA and CPF is the cost of product assembly and finishing (including testing, certifying, and final assembly, labelling and painting etc. assumed to be single value specific to the product family). Miscellaneous other costs will be assumed to be absorbed by others in this model.

$$CRF = CPR + CPD + CCS + CCR + CCU + CCC + CCD + CPA + CPF \tag{6.2}$$

The CPR (Eq.6.3) can be calculated from the shipping costs, cs, of product i per kilometre, and the distance, l between the product location, available from the DT, and the remanufacturing facility, f.

$$CPR = cs_i l_f \tag{6.3}$$

The CPD (Eq.6.4) relates to whether component j needs to be disassembled from the product nd, the cost of disassembly per unit of time cd, the time it takes to disassemble td, a time function TQ_1 given product quality, from the DT, of q_i, and the time function TS assuming that more time will be taken to disassemble products into components destined for a second life via remanufacturing or reuse sl, over those that will be recycled or disposed of, nsl. With the CAD, BoM and component relationship information available in the DT, the disassembly sequence

can be extracted to match the requirements of the remanufacturing demand. Comprehensive lists of attributes for disassembly in remanufacturing can enable the integration of such systems (NISTIR, 2011).

$$CPD = \sum_{j} (nd_j cd_j td_j (TSsl_j + nsl_j) TQ_1) \tag{6.4}$$

The CCS (Eq.6.5) result from the need to hold components nh, that have been identified as having second life potential but cannot be used in the existing product and are also not recycled or disposed of. If component j needs to be stored nh, ch is the cost of holding per unit of time and th is the time in storage then,

$$CCS = \sum_{j} (nh_j (ch_j th_j + cph_j)) \tag{6.5}$$

Following disassembly or recovery from storage, the components can take one of four remanufacturing option routes (decision variables) through reincarnation, reuse, recycling or disposal. ro_x represents the routes where $x \in \{1,2,3,4\}$ respectively. As described previously, the reincarnation processes, CCR (Eq.6.6), in the remanufacturing function refer to the repair, upgrade, rebuild etc. of the product or hybrid of components to match, or better, the quality of a new equivalent. Having already been disassembled, the components may need to be cleaned, machined (additive or subtractive) or repaired nr. An estimation of the work that may be required could be made in the process DT using the information from the product DT comparing the 'as manufactured' with the 'current state' instances. Herein offers an opportunity to map product requirements to process capabilities to create suitable production plans. The cost per unit of time in reincarnation is cr. The time tr to complete these reincarnation activities, is affected by the quality of the received component. An estimate of product quality is provided by the DT as q_i (in Chapter 5 this was referred to simply as Q) but the component quality will

depend on the MoL environment and utilisation. A DT at component level, or inferred quality from the performance metrics and / or failure mode data, would need to be available to estimate component RUL and quality. This was not demonstrated in the previous chapters, but it is assumed to be possible with improvements in data analytics, diagnostics and prognostics. In order to continue, $q_j = q_i$ in this model and a time function TQ_2 that translates the impact of the different quality levels on time taken to reach q_{min} will be applied, where q_{min} is the minimum quality needed for the component to be successfully incorporated into a remanufactured product. Once ready for re-assembly components can be built into products alongside new (procurement) or spare parts (reuse) if needed. CCP (Eq.6.7) is the total component purchasing costs where the costs to procure a part or service cp to replace one that will be retained for reuse, has failed, is damaged, is consumable, or upgradable (with the original destined for recycling or disposed), or is missing m when the product was recovered, are also included.

$$CCR = ro_{j1} = \sum_j nr_j(TQ_2 cr_j tr_j) + CCP \tag{6.6}$$

Where,

$$CCP = \sum_j cp_j(ro_{j2} + ro_{j3} + ro_{j4} + m_j) \tag{6.7}$$

With the parts already disassembled, there may be cost associated with preparing a component for reuse CCU (Eq.6.8), related to time tu and quality q_j to feed into either the reincarnation fr_j or reuse fu_j flow. Additionally, as P in Eq.6.1 only considers the remanufactured product, CCU includes the revenue generated from the sale of components directly cru_j.

$$CCU = ro_{j2} = \sum_{j} nu_j(TQ_3 cu_j tu_j(fr_j + fu_j) - cru_j) \tag{6.8}$$

The cost of recycling CCC (Eq.6.9) comes from the sum of the costs minus the material sales revenue mrc from the component in question nc. Material level data and component weights from the DT BoM enable this assessment. Product level recycling is not considered as it is assumed the product is only recovered from the end-user if it has remanufacturing potential. It is also assumed that this activity is a transaction, and the process of recycling is out of scope.

$$CCC = ro_{j3} = \sum_{j} nc_j(cc_j - mrc_j) \tag{6.9}$$

Similarly, the cost of component disassembly CCD (Eq.6.10) includes disposal cost cdp for components set for this route only ndp. No revenue opportunities are expected from the disposal option. Component weights from the DT may support this.

$$CCD = ro_{j4} = \sum_{j} ndp_j cdp_j \tag{6.10}$$

As the aim is to build a unit for market, the cost of product assembly CPA (Eq.6.11) with na representing the components required to assembly the new product, the total costs per unit of time incurred from assembling is expressed in ca and the time is ta.

$$CPA = \sum_{j} na_j ca_j ta_j \tag{6.11}$$

Constraints are similar to those used in Meng *et al.* (2017) and are documented in Eq.6.11 – 6.19. Eq. 6.11 states that each component can either be included 1, or not 0 from disassembly, storage, reincarnation, reuse, recycling, or disposal. Eq.6.12 limits each component to only one of the remanufacturing options x, but at least one component needs to be disassembled and

processed through ro_1 to meet the product demand Eq.6.13, but Eq.6.14 ensures the number of components disassembled is less than or equal to the total number of parts z in the assembled product i. Eq.6.16 relates to the predecessors in the disassembly process. Eq.6.17 limits the flow of components through reuse to either reincarnation or reuse ready for sale, whilst Eq.6.18 balances the number of components not destined for second life with those that are recycled or disposed of. Eq.6.19 constrains the time functions λ, to real numbers greater than zero.

$$fr_j, fu_j, m_j, nd_j, nsl, nh_j, nr_j, nu_j, nc_j, ndp_j sl \in \{0,1\} \tag{6.12}$$

$$\sum_x ro_{jx} = 1 \quad \forall j \tag{6.13}$$

$$\sum_j nd_j \geq ro_{j1} \geq 1 \tag{6.14}$$

$$\sum_j nd_j \leq z \tag{6.15}$$

$$nd_j \geq nd_k \quad \forall j \in P_k \tag{6.16}$$

$$\sum_j (fr_j + fu_j) = 1 \quad \forall j \tag{6.17}$$

$$nsl_j = \sum_j (nc_j + ndp_j) \tag{6.18}$$

$$\lambda = TS, TQ_1, TQ_2, TQ_3 \ \{\lambda \in \mathbb{R} \,|\lambda > 0\} \tag{6.19}$$

6.2.2.2 Evaluating the Environmental Stewardship Impact in the DMM

The potential environmental benefits, E result from the environmental savings made through remanufacturing a product and making it available to the customer, as opposed to one made

from virgin material and processes ES, minus the impact to the environment from the remanufacturing function, ERF (Eq.6.20).

$$E = ES - ERF \tag{6.20}$$

Referencing Figure 6-2 the ERF includes the environmental impacts of product recovery, EPR, disassembly, EPD, component storage, ECS, reincarnation activities, ECR, reuse, ECU, recycling, ECC, disposal, ECD, assembly, EPA and product finish, EPF (Eq.6.21). EPF is the environmental impacts of product finishing assumed to be single value specific to the product family. Miscellaneous other environmental impacts such as those from facility systems will be assumed to be absorbed by others in this model.

$$ERF = EPR + EPD + ECS + ECR + ECU + ECC + ECD + EPA + EPF \tag{6.21}$$

Environmental impacts can be categorised as energy (J) and material consumption (kg), emissions to air and water (kg), and waste generation (kg) (Smith and Keoleian, 2004). These can be referred to as environmental impact $e\alpha_y$ where α is the action (shipping, disassembly, storage etc.) and $y \in \{1,2,3,4,5\}$ reflecting the impact categories, respectively. The EPR (Eq.6.22) can then be calculated from the environmental impacts of shipping es that will likely include the energy consumption from fuel and emissions to air (Eq.6.19) for the journey between the product and facility locations available from the DT.

$$EPR_y = es_{yi} l_f \tag{6.22}$$

The EPD (Eq.6.23) relates to the environmental impact of disassembly of component j per unit of time ed and the time it takes to disassemble td. Energy consumption is likely to be a key impact in both automated and semi-automated disassembly processes in the remanufacturing I4.0 of the future as electronic and/or pneumatic tooling will be prevalent and demanding of

sub-stations or compressor units. The scale of the impact will be proportional to utilisation time. The joining methods and attributes such as tightening torques can be extracted from the DT to estimate separation, tooling and fixturing energy requirements.

$$EPD_1 = \sum_j (nd_j ed_{y1j} td_j (TSsl_j + nsl_j) TQ_1 q_i) \tag{6.23}$$

The ECS (Eq.6.24) result from the potential need to preserve components for storage. This can often utilise materials and generate solid waste from bagging, or if a protective coating is applied directly, emissions to water via application or energy consumption and pollutants from the wash-off process. Depending on the time in storage multiple applications or layering of methods may be required. Material properties, of components can be extracted from the 'as designed' DT to direct preservation methods. Therefore, if component j needs to be stored, eh is the environmental impact of holding per unit of time and th is the time in storage then,

$$ECS_y = \sum_j (nh_j eh_{yj} th_j) \tag{6.24}$$

The four remanufacturing option routes remain the same as in section 6.2.2.1. As already presented, within the reincarnation activity, components may need to be cleaned, machined (additive or subtractive) or repaired, before assembly, testing and finishing can occur. Many of these processes will come with environmental impact and the potential for all five categories being represented. Examples include powering spindles, water for coolant systems in machine tools, the heating and use of wash solutions in cleaning, the addition of new materials or replacement parts, product testing emitting emissions, wastewater and heat energy, or volatile organic compounds from paint applications. Estimations for these activities can be made by comparing the current and future state DTs.

The environmental impact per unit of time in reincarnation is er. *ECP* (Eq.6.26) is the environmental impact associated with the procurement of a part or service to replace one that will be retained for reuse, has failed, is upgradable, or is missing ep.

$$ECR_y = ro_{j1} = \sum_j nr_j(TQ_2 q_j er_{yj} tr_{j_{yj}}) + ECP \tag{6.25}$$

Where,

$$ECP_y = \sum_j ep_{yj}(ro_{j2} + ro_{j3} + ro_{j4} + m_j) \tag{6.26}$$

Similar to the equivalent costing equations in section 6.2.2.1, there could be some environmental impact generated as a result of preparing a component for reuse eu, and these ought to be evaluated as reusing a product does not guarantee an environmental benefit (Cooper and Gutowski, 2017). However, these impacts are likely to be less than those associated with reincarnation, recycling and disposal as this option is generally associated with a lower level of product change, energy expenditure and value leakage (Ellen MacArthur Foundation, 2013). As E in Eq.6.20 only considers the remanufactured product, ECU (Eq.6.27) captures the environmental benefits associated with reusing the component over a new component *e*ru.

$$ECU_y = ro_{j2} = \sum_j nu_j(TQ_3 eu_{yj} tu_j(fr_j + fu_j) - eru_{yj} \tag{6.27}$$

The environmental impacts of component recycling ECC (Eq.6.28) comes from the energy and materials used and wastes generated when returning a component back to a useable material. The total benefits associated with reusing the material over virgin material *e*rc are also considered.

$$ECC_y = ro_{j3} = \sum_j nc_j(ec_{yj} - erc_j) \tag{6.28}$$

Similarly, the environmental impact of disposal edp include emissions to water and solid waste for those components set for this route only ndp. As disposal is recognised as the last option in the CE loop (Korhonen, Honkasalo and Seppälä, 2018) no environmental benefits are expected. The weight of solid waste can be predicted using the material and CAD data, whilst the water waste estimate may need to come from a measured or inferred value, both made available in the current state DT.

$$ECD = ro_{j4} = \sum_j ndp_j edp_{yj} \tag{6.29}$$

The environmental impacts incurred from assembling and testing etc. are expressed in ea. The 'as manufactured' DT can support here.

$$EPA = \sum_j na_j ea_{yj} ta_j \tag{6.30}$$

Constraint equations Eq.6.12-6.19 are applicable.

6.2.2.3 Evaluating the Social Wellbeing Impact in the DMM

As previously discussed, the social pillar of sustainability is the least researched to date. Therefore, the equations that drive this element of the evaluation will be based on the three distinct social groups, the employee, customer, and community (Joung *et al.*, 2013). The first will be based on job opportunities similar to that proposed by Meng *et al.* (2017) but instead of being dependant on the weight of recoverable material it will use time. This works on the assumption that tasks requiring longer to perform than others within the scope already defined,

are proportional to the number of people that could be employed to complete the task. In this regard, the more people that can be employed the better it is for society.

The second element is driven by the relationship between the customer / user and remanufacturer and made possible by the DT. As described in section 5.4.5 the customer can make the DT data available to EoL service providers when they no longer require the product, so that remanufacturers can evaluate processing options. The remanufacturer uses this data to decide on whether or not to recover the HiVE. This places data driven decision-making at the forefront of remanufacturing planning, but if the remanufacturer decides not to recover the HiVE, it may become an unwanted burden to the user. This would be seen as having negative social impact.

The final element relates to community impact and is based on the relationship between reused or remanufactured components and recycled material, to that being discarded. The greater quantity, volume or weight of material going through remanufacturing or recycling compared to disposal, the better it is for society.

Starting with the employees, of the remanufacturing activities segregated in Figure 6-2 there are four that include time variables. These are disassembly, storage, reincarnation, and reuse. Assuming all man-hours H are valued the same, then J is the function that relates process time to man-hours.

$$\mathrm{H} = \sum_{j} J_j(td_j + ts_j + tr_j + tu_j) \tag{6.31}$$

With regards to the burden, B of managing a product offered up the remanufacturing business, the impact positive if the remanufacturing business recovers it, or negative if it does not.

$$\mathrm{B} = \in \{-1,1\} \tag{6.32}$$

Finally, the volume-based ratio of reused, remanufactured, and recycled material V_r to those going to disposal V_d is R.

$$\mathrm{R} = \frac{V_r}{V_d} \tag{6.33}$$

A single value related to the social impact S is required. To ensure that each element is represented accordingly, a weighted deviation method based on Dehghanian and Mansour (2009) can be used as described in Eq.6.34.

$$WD_s = \sum_{n=1}^{3} w_n \left(\frac{\left| f_n^{(s)} - f_n^{*} \right|}{f_n^{*}} \right) \tag{6.34}$$

The weighted deviation (WD) utilises the distance between the solution and the ideal to find the best match for the decision-makers requirements. If n represents the three elements H, B and R, w_n are the weightings applied to n by the business. $f_n^{(s)}$ and $f_n^{(*)}$ are the nth objective function values of solution, s, and the ideal, $*$. The lower the WD, the closer it is to the decision-makers request.

This model has focused on the CE's triple bottom line but does not include the extended 'technological advancement' or 'performance management' elements as clarity on how these may be quantified is lacking in literature. Research development, the advancement of high-tech products, conformance to guidelines, programmes and policies are all relevant and have the potential to influence the desire to remanufacture with incentives or secondary market drivers. Also not considered in the model is resource allocation and availability, both are assumed to be finite.

6.2.3 Model Evaluation Method

The DMM will aim to optimise the disassembly sequence and provide the most cost-effective remanufacturing function for each component based on the raw data in Appendix E . The raw data includes a high-level list of parts and disassembly process predecessors, a component interference matrix built as per Percoco and Diella (2013) and a set of values for populating the calculation.

This type of nondeterministic polynomial-time complete problem crosses disciplines and appears to be well researched (Wang *et al.*, 2013), including in the lesser studied sectors like remanufacturing as documented recently in Zhou *et al.* (2019). There are many manual and automated methods available that can be enhanced or hybridised to improve solution speed, search space and / or accuracy. Nature-inspired algorithms (NA) appear to be the most prominent and include ant, bee, and fruit-fly colony optimisation as well as immune response and particle swam inspired methods. A key area of research running parallel to the AUTOREMAN project at the University of Birmingham relates to the Bees Algorithm (BA) developed by Pham *et al.* (2005). A MATLAB version of this tool by Hartono (2021) is utilised in the DMM to calculate the best disassembly sequence solution, the routing, and the cost associated with each targeting the minimisation of CRF.

6.2.4 Case Study

Following on from Chapter 4 and backed by the lessons learned in Chapter 5, the numerical demonstration utilises a large industrial engine as a case study. At around 2T in weight they are of high material value with long life cycles. Many remain in service after 20 years. The information for this case study is gathered from interviews with experienced assembly and strip mechanics, process engineers, freely available technical literature and cross referenced with data from Smith and Keoleian (2004).

The disassembly process taken by the operations team is highly dependent on the target component(s) and the state of the core. With almost 4000 components in the BoM for this case study product, the designers have worked hard to design-for-disassembly to facilitate servicing, so the amount of inter-connectivity between the parts is limited. However, the nature of the diesel engine makes for some complicated assemblies that have been simplified significantly for this assessment. There are a number of different routes that can be taken in many scenarios, but the main disassembly relationship structure used in this demonstration is shown in Figure 6-3.

For this case study, complete disassembly of the EoL core and rebuild to form one remanufactured product, has been assumed. From the relationship matrix a list of predecessors (Table 7-10) and an interference matrix (Table 7-11) can be generated. The objective function is to minimise the CRF in Eq.6.1 so the optimal solution (OS) is

$$OS = \min\,(CRF) \tag{6.35}$$

The constraint equations have already been defined Eq.6.12-6.19. Raw data used in the model can be found in Table 7-2 to Table 7-6 in Appendix E.

6.2.5 Model Verification

To verify the Hartono (2021) model and its use in the DMM, the script was modified to utilise a single set of data from the HiVE-DTP with a pre-defined component routing. Components were identified as 1-40 and their potential routings were 1 = reuse, 2 = reincarnation, 3 = recycle and 4 = dispose. The results were compared to a manual assessment (Table 7-7 to Table 7-9 in Appendix E) of the same data stream.

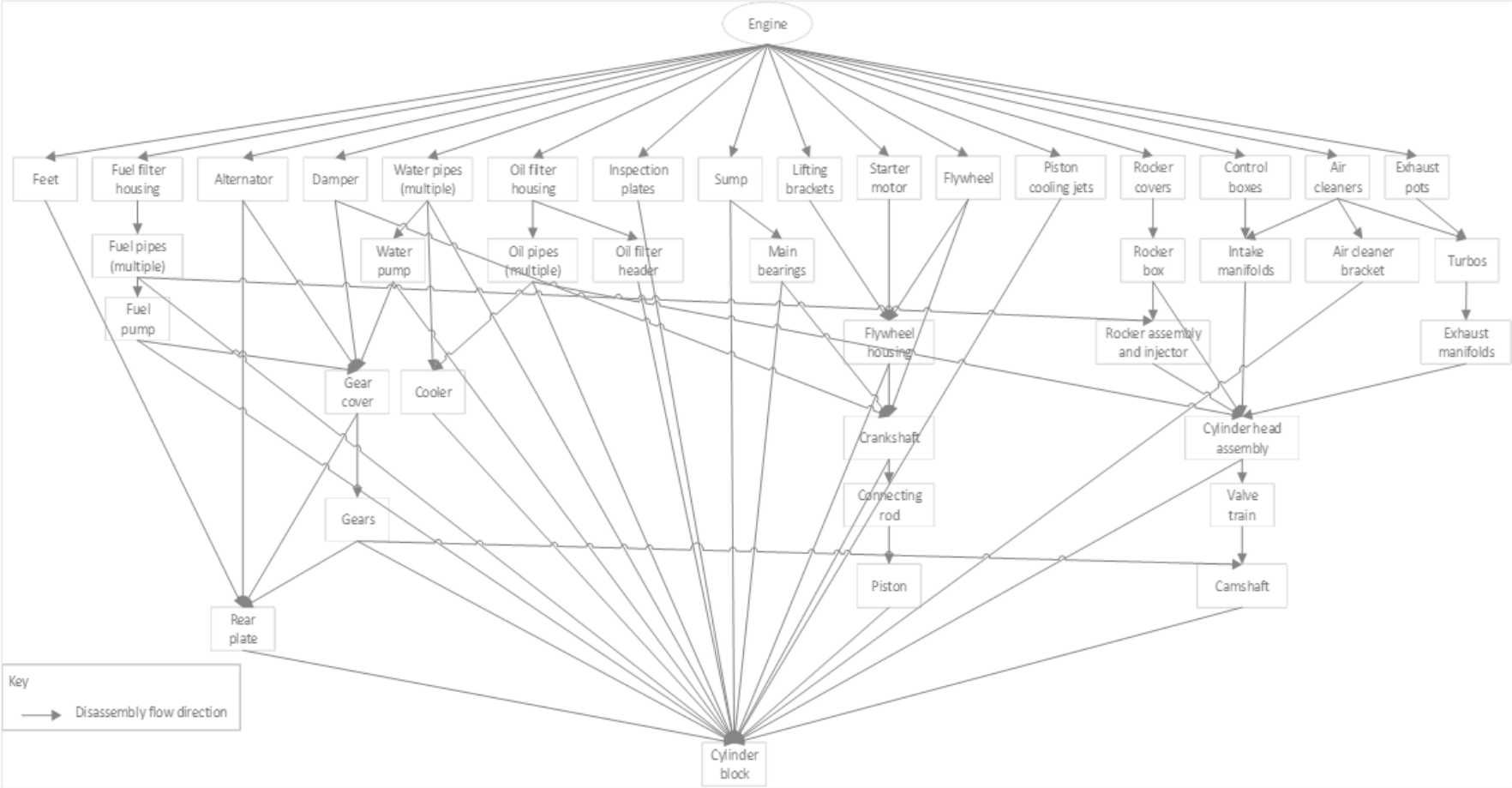

Figure 6-3 High-level disassembly precedence relationship between engine components

The CRF from both the manual and computated model was £29,058.84. With a newly manufactured product sales price of circa £38,000, a remanufactured goods sales price of 20-40% below (Invest NI, 2017) would result in a target selling price of £26,600 (30% of new). The two non-optimised calculated costs to remanufacture a product with q = 0.543, with latitude and longitude of the product and remanufacturing facility of 51.5074,0.1278 and 52.7101,-2.7521 respectively (data provided from the DT), and using MATLAB's Mapping Toolbox deg2km function, the resulting costs of £29,058.84 demonstrated that the model was valid and its proximity to the target selling price suggested it had the potential to generate profit making solutions with the raw data available. Two runs of the DMM are displayed in Table 6-2 including the sequence of disassembly, routing of components and the associated costs. Both disassembly sequences were assessed manually and declared viable.

Table 6-2 DMM algorithm output and validation

Result using Fix route (mode: U = 1, R = 2, C = 3, D = 4)																					
Run 1																					
Step	***1***	***2***	***3***	***4***	***5***	***6***	***7***	***8***	***9***	***10***	***11***	***12***	***13***	***14***	***15***	***16***	***17***	***18***	***19***	***20***	
Sequence	27	16	38	25	5	14	36	13	34	28	37	9	11	35	39	4	32	30	33	23	
Mode	4	1	3	3	4	2	4	3	3	2	3	1	2	4	1	1	1	1	3	3	
Step	***21***	***22***	***23***	***24***	***25***	***26***	***27***	***28***	***29***	***30***	***31***	***32***	***33***	***34***	***35***	***36***	***37***	***38***	***39***	***40***	
Sequence	24	19	3	29	15	40	21	22	18	31	17	20	2	26	10	7	6	12	8	1	
Mode	3	1	4	3	3	1	3	3	3	1	3	3	2	1	2	2	3	2	3	2	
BestCost (£)																					29058.844
Run 2																					
Step	***1***	***2***	***3***	***4***	***5***	***6***	***7***	***8***	***9***	***10***	***11***	***12***	***13***	***14***	***15***	***16***	***17***	***18***	***19***	***20***	
Sequence	5	38	30	13	25	24	27	28	23	32	9	17	26	16	15	40	39	4	14	36	
Mode	4	3	1	3	3	3	4	2	3	1	1	3	1	1	3	1	1	1	2	4	
Step	***21***	***22***	***23***	***24***	***25***	***26***	***27***	***28***	***29***	***30***	***31***	***32***	***33***	***34***	***35***	***36***	***37***	***38***	***39***	***40***	
Sequence	35	33	29	22	21	34	37	19	20	3	18	11	31	10	2	7	6	8	12	1	
Mode	4	3	3	3	3	3	3	1	3	4	3	2	1	2	2	2	3	3	2	2	
BestCost (£)																					29058.844

6.2.6 Model Optimisation

In a fully automated disassembly cell the sequence, as long as it was viable, would matter less as the system memory would manage the process and have awareness of all components and product build level. However, the process data used in this case study is based on human disassembly. Whilst the sequences generated and presented in Table 6-2 were viable they did not offer a logical structure for human managed disassembly. Following the sequence suggested by the algorithm, would demand the operator to change the direction and logical flow of the work content. To weigh the disassembly process to drive a more human friendly solution, a disassembly matrix was generated that applied a penalty to a change in disassembly direction of +1min for 90º and +2mins for 180 º. The disassembly time matrix can be found in Table 7-12.

In addition, the model was designed to allow the remanufacturing routings to be managed in two ways. Firstly a 'fixed' mode that enabled the routings to be pre-defined which would suit already established or in-flexible processes. This mode was used to validate the results with the manual process. Secondly, a 'self-assigned' mode that works to identify the best routing available from the potential options, as defined in the raw data, suitable for flexible disassembly and management processes. Results in section 6.3 utilise the 'self-assigned' mode.

6.3 Results

All results are documented in Table 7-13 to Table 7-56, Appendix E . A sample of the DMM output at $q = 1$ is presented across Table 6-3 to Table 6-6. As can be seen from Table 6-3 and Table 6-4 the BA works to identify the disassembly sequence that provides the cheapest remanufacturing function cost for the inputs provided. Similarly, it looks to optimise the routing of the components to minimise expenditure (Table 6-5 and Table 6-6).

Table 6-3 Bees Algorithm generated disassembly sequence results at q=1 (1/2)

Quality (q)	Distance (km)	Disassembly sequence (by Part Number)																																									
1	0	13	32	17	35	9	15	39	24	38	25	16	21	14	30	11	26	5	10	4	23	22	40	36	7	34	27	3	33	28	20	2	37	29	8	6	19	18	12	31
1	100	39	38	14	13	9	5	32	25	17	27	33	35	4	24	26	30	16	11	15	23	28	22	10	20	40	36	7	34	3	21	29	8	37	2	19	18	6	12	31
1	200	39	13	27	33	9	15	35	38	40	16	22	11	36	34	25	24	14	30	5	21	17	37	4	20	28	23	3	32	29	2	6	26	10	19	7	18	12	31	8
1	300	39	24	35	16	17	38	5	27	14	28	32	30	4	9	13	23	11	15	33	25	40	22	20	26	29	10	36	7	34	8	37	19	21	3	2	18	6	31	12
1	400	39	35	14	27	16	36	38	34	33	37	13	25	5	17	4	9	15	24	26	21	30	32	22	20	11	10	3	40	28	23	2	6	29	19	7	8	18	12	31
1	500	39	36	24	5	13	14	34	17	37	38	9	35	16	27	33	32	4	28	11	15	3	22	40	21	20	25	26	10	7	8	2	30	23	19	18	29	31	6	12
1	600	39	35	5	24	25	13	4	27	9	15	38	16	32	17	26	22	30	21	14	36	11	20	28	33	34	40	37	29	10	7	8	3	23	2	6	19	18	31	12
1	700	39	14	24	17	32	5	13	25	26	4	35	16	9	38	30	11	15	22	40	10	36	7	27	21	28	8	34	23	3	37	33	29	20	2	19	6	18	31	12
1	800	13	39	9	36	38	17	32	34	16	27	37	11	15	24	40	14	35	5	30	22	33	28	4	25	21	20	3	23	19	29	26	18	2	31	10	6	12	7	8
1	900	13	5	25	4	24	9	30	17	39	14	23	16	26	11	10	15	36	7	34	35	3	27	22	8	37	28	19	33	40	29	32	20	38	21	2	18	31	6	12
1	1000	13	39	5	32	17	38	9	27	24	4	35	25	11	15	16	22	40	26	20	33	30	28	21	29	14	23	10	36	7	8	34	3	37	2	6	19	18	31	12
1	1100	39	13	30	35	17	23	16	25	26	14	9	15	38	22	40	24	20	5	36	34	37	11	4	10	19	7	3	32	27	28	18	31	33	29	8	21	2	6	12
1	1200	39	24	27	16	35	9	11	15	36	40	25	14	30	5	4	21	32	22	33	28	17	20	13	26	29	34	38	37	23	10	7	19	3	2	8	6	18	12	31
1	1300	13	36	39	30	14	24	27	34	35	9	5	11	15	37	16	17	33	22	32	38	4	20	28	23	3	21	19	29	2	40	25	6	18	31	12	26	10	7	8
1	1400	13	25	39	5	24	36	14	30	35	38	16	27	23	9	34	28	11	15	17	40	37	21	19	33	4	32	3	26	10	22	18	7	20	29	2	31	6	8	12
1	1500	39	14	27	17	33	36	24	30	23	9	15	11	34	37	35	21	16	5	32	13	38	28	4	25	22	40	26	3	10	20	29	7	8	19	18	2	6	12	31
1	1600	39	27	14	16	9	15	17	24	22	38	36	34	5	32	11	30	23	35	13	37	19	18	21	28	33	29	4	40	31	25	20	26	10	3	7	8	2	6	12
1	1700	13	27	9	15	33	17	11	24	25	5	4	38	26	14	35	21	16	10	36	7	40	22	34	8	3	37	20	30	23	28	39	2	29	19	6	32	18	31	12
1	1800	13	25	17	39	5	27	35	33	14	30	23	24	9	11	15	28	4	16	40	22	20	29	38	26	10	36	7	34	37	32	8	3	19	18	31	21	2	6	12
1	1900	39	35	13	17	24	36	27	30	38	32	16	34	33	25	14	37	9	15	28	26	21	23	11	29	22	19	20	5	18	10	4	7	31	3	8	2	6	40	12
1	2000	39	36	14	27	33	24	16	13	9	35	30	23	25	32	28	34	29	11	15	17	40	22	21	5	37	20	4	3	2	19	38	18	6	12	26	31	10	7	8
1	2100	13	24	30	23	14	17	36	32	27	33	28	35	39	9	15	11	34	38	16	37	19	18	25	40	5	21	22	4	29	26	31	20	3	2	6	10	12	7	8
1	2200	39	36	5	27	33	4	35	9	15	11	34	32	17	13	16	14	22	38	25	3	21	30	26	28	23	20	29	37	24	2	40	10	19	6	18	31	7	12	8
1	2300	39	9	25	27	28	13	11	15	32	30	24	14	16	40	22	23	35	5	4	21	38	33	36	29	34	17	26	20	10	3	37	19	18	31	2	7	6	12	8
1	2400	39	16	24	32	30	36	23	9	27	11	15	17	33	5	25	38	34	37	35	21	14	19	40	22	13	28	29	20	26	10	18	31	7	8	4	3	2	6	12
1	2500	13	35	9	17	39	32	14	11	15	30	25	38	26	5	40	16	22	10	36	7	23	4	27	24	20	33	21	34	3	2	8	6	28	37	19	29	18	12	31

Table 6-4 Bees Algorithm generated disassembly sequence results at q=1 (2/2)

Quality (q)	Distance (km)	Disassembly sequence (by Part Number)																																								
1	2600	39	35	9	38	11	15	24	17	27	33	36	28	5	30	23	16	4	29	21	34	14	37	40	32	3	19	22	20	2	6	25	18	31	12	13	26	10	7	8
1	2700	39	27	38	5	24	9	15	16	13	32	11	25	14	28	33	40	4	22	17	30	23	29	35	20	26	21	10	36	7	8	34	3	37	2	6	19	18	31	12
1	2800	13	36	39	30	38	34	37	23	25	14	17	35	26	24	5	9	27	32	33	28	4	29	3	11	15	19	40	16	10	22	7	18	20	31	21	8	2	6	12
1	2900	39	13	24	17	14	30	27	23	5	16	25	33	35	38	9	28	11	26	4	10	15	36	7	29	40	8	22	21	32	20	34	3	2	6	37	19	18	12	31
1	3000	39	5	16	25	27	33	32	36	35	28	34	38	37	9	15	22	24	40	17	21	14	4	30	3	20	13	26	2	6	29	23	19	18	12	11	10	31	7	8
1	3100	13	25	39	5	9	15	16	38	32	11	30	17	27	24	26	28	33	35	14	40	23	10	36	7	29	22	4	20	8	21	34	3	37	2	6	19	18	31	12
1	3200	13	27	30	17	32	39	14	28	33	9	29	11	15	24	38	25	23	26	35	21	40	16	5	10	36	7	8	22	4	20	34	37	3	2	6	19	18	12	31
1	3300	13	16	25	32	35	5	38	36	39	24	34	9	17	26	27	28	11	15	37	22	30	20	40	21	23	14	33	19	18	29	10	7	4	31	8	3	2	6	12
1	3400	39	35	9	15	16	17	24	22	27	40	13	32	30	38	5	25	14	4	20	11	26	28	33	10	29	36	7	8	21	34	23	3	37	19	18	31	2	6	12
1	3500	13	17	25	9	27	16	24	28	35	14	26	5	33	32	11	10	15	38	40	4	21	22	20	39	36	7	30	8	29	34	3	37	23	19	2	18	6	31	12
1	3600	39	5	14	32	4	36	13	9	15	30	25	17	35	26	38	16	34	27	28	3	40	22	20	24	37	23	19	33	21	29	11	10	7	8	18	31	2	6	12
1	3700	13	9	39	38	30	32	27	28	24	11	15	17	25	5	16	23	26	14	4	10	35	22	21	20	40	33	36	7	34	8	29	37	19	3	18	31	2	6	12
1	3800	39	25	17	16	24	27	5	13	38	32	28	4	9	14	11	15	26	30	10	22	40	36	7	33	8	29	20	35	34	21	37	23	3	2	6	19	18	31	12
1	3900	39	5	24	16	32	30	4	27	14	25	9	17	11	15	13	36	28	35	26	38	22	23	33	29	34	20	21	3	37	10	7	8	40	2	6	19	18	31	12
1	4000	39	9	27	14	30	38	35	32	13	16	24	11	17	25	23	26	10	15	36	7	33	21	28	34	37	8	40	29	19	18	31	5	4	3	22	20	2	6	12
1	4100	13	17	9	15	38	36	27	32	39	5	40	35	16	28	25	22	30	23	14	26	11	21	20	4	10	7	24	33	8	29	34	3	37	2	6	19	18	31	12
1	4200	39	16	27	9	15	5	40	25	32	13	22	38	4	35	14	36	21	11	34	28	33	30	24	3	23	29	17	26	10	7	8	37	19	18	31	20	2	6	12
1	4300	13	9	16	27	28	38	30	36	17	25	26	35	32	11	15	24	40	33	5	4	29	34	39	14	23	37	10	3	22	20	21	19	7	18	31	2	8	6	12
1	4400	13	5	16	35	17	9	27	38	11	15	14	32	33	4	39	21	25	26	10	22	28	40	24	30	20	29	23	36	7	34	3	2	8	37	6	19	18	12	31
1	4500	13	25	32	27	16	38	28	5	24	39	36	17	26	9	15	22	14	4	40	33	30	11	35	34	29	20	37	3	10	21	2	7	6	8	23	19	18	12	31
1	4600	39	17	27	36	9	15	25	38	28	34	40	30	13	23	37	14	16	24	35	21	5	26	4	22	20	32	19	3	33	18	29	11	10	7	2	31	6	8	12
1	4700	39	36	17	34	9	16	32	35	27	28	14	24	25	5	11	15	4	30	22	40	13	38	23	37	3	19	18	26	10	31	21	20	7	8	33	2	29	6	12
1	4800	13	17	25	9	15	35	26	16	27	30	22	23	11	14	5	39	4	33	28	10	32	40	36	7	24	38	20	34	21	3	29	2	37	19	18	8	31	6	12
1	4900	13	35	25	9	15	36	14	27	34	11	17	16	38	33	40	24	30	32	37	22	23	21	39	28	29	26	5	10	7	8	4	20	3	19	18	31	2	6	12
1	5000	39	27	17	28	32	24	13	5	38	25	35	9	15	11	33	21	26	30	29	23	14	10	16	36	7	4	22	34	40	37	20	19	18	31	3	2	8	6	12

Table 6-5 Bees Algorithm generated routing and costs related to sequences in Table 6-3

Quality (q)	Distance (km)	Remanufacturing Method (1=Reuse, 2=Reincarnate, 3=Recycle, 4=Disposal)																																											Cost (£)
1	0	3	1	3	4	1	3	1	3	3	3	1	3	2	1	2	1	4	2	1	3	3	1	4	2	3	4	4	3	2	3	2	3	3	3	3	1	3	2	1	2	23,921
1	100	1	3	2	3	1	4	1	3	3	4	3	4	1	3	1	1	1	2	3	3	2	3	2	3	1	4	2	3	4	3	3	3	3	2	1	3	3	2	1	2	23,937
1	200	1	3	4	3	1	3	4	3	1	1	3	2	4	3	3	3	2	1	4	3	3	3	1	3	2	3	4	1	3	2	3	1	2	1	2	3	2	1	3	2	23,957
1	300	1	3	4	1	3	3	4	4	2	2	1	1	1	1	3	3	2	3	3	3	1	3	3	1	3	2	4	2	3	3	3	1	3	4	2	3	3	1	2	2	23,969
1	400	1	4	2	4	1	4	3	3	3	3	3	3	4	3	1	1	3	3	1	3	1	1	3	3	2	2	4	1	2	3	2	3	3	1	2	3	3	2	1	2	23,989
1	500	1	4	3	4	3	2	3	3	3	3	1	4	1	4	3	1	1	2	2	3	4	3	1	3	3	3	1	2	2	3	2	1	3	1	3	3	1	3	2	2	24,005
1	600	1	4	4	3	3	3	1	4	1	3	3	1	1	3	1	3	1	3	2	4	2	3	2	3	3	1	3	3	2	2	3	4	3	2	3	1	3	1	2	2	24,021
1	700	1	2	3	3	1	4	3	3	1	1	4	1	1	3	1	2	3	3	1	2	4	2	4	3	2	3	3	3	4	3	3	3	3	2	1	3	3	1	2	2	24,032
1	800	3	1	1	4	3	3	1	3	1	4	3	2	3	3	1	2	4	4	1	3	3	2	1	3	3	3	4	3	1	3	1	3	2	1	2	3	2	2	3	2	24,053
1	900	3	4	3	1	3	1	1	3	1	2	3	1	1	2	2	3	4	2	3	4	4	4	3	3	3	2	1	3	1	3	1	3	3	3	2	3	1	3	2	2	24,064
1	1000	3	1	4	1	3	3	1	4	3	1	4	3	2	3	1	3	1	1	3	3	1	2	3	3	2	3	2	4	2	3	3	4	3	2	3	1	3	1	2	2	24,080
1	1100	1	3	1	4	3	3	1	3	1	2	1	3	3	3	1	3	3	4	4	3	3	2	1	2	1	2	4	1	4	2	3	1	3	3	3	3	2	3	2	2	24,100
1	1200	1	3	4	1	4	1	2	3	4	1	3	2	1	4	1	3	1	3	3	2	3	3	3	1	3	3	3	3	3	2	2	1	4	2	3	3	3	2	1	2	24,116
1	1300	3	4	1	1	2	3	4	3	4	1	4	2	3	3	1	3	3	3	1	3	1	3	2	3	4	3	1	3	2	1	3	3	3	1	2	1	2	2	3	2	24,132
1	1400	3	3	1	4	3	4	2	1	4	3	1	4	3	1	3	2	2	3	3	1	3	3	1	3	1	1	4	1	2	3	3	2	3	3	2	1	3	3	2	2	24,148
1	1500	1	2	4	3	3	4	3	1	3	1	3	2	3	3	4	3	1	4	1	3	3	2	1	3	3	1	1	4	2	3	3	2	3	1	3	2	3	2	1	2	24,164
1	1600	1	4	2	1	1	3	3	3	3	3	4	3	4	1	2	1	3	4	3	3	1	3	3	2	3	3	1	1	1	3	3	1	2	4	2	3	2	3	2	2	24,180
1	1700	3	4	1	3	3	3	2	3	3	4	1	3	1	2	4	3	1	2	4	2	1	3	3	3	4	3	3	1	3	2	1	2	3	1	3	1	3	1	2	2	24,191
1	1800	3	3	3	1	4	4	4	3	2	1	3	3	1	2	3	2	1	1	1	3	3	3	3	1	2	4	2	3	3	1	3	4	1	3	1	3	2	3	2	2	24,207
1	1900	1	4	3	3	3	4	4	1	3	1	1	3	3	3	2	3	1	3	2	1	3	3	2	3	3	1	3	4	3	2	1	2	1	4	3	2	3	1	2	2	24,227
1	2000	1	4	2	4	3	3	1	3	1	4	1	3	3	1	2	3	3	2	3	3	1	3	3	4	3	3	1	4	2	1	3	3	3	2	1	1	2	2	3	2	24,243
1	2100	3	3	1	3	2	3	4	1	4	3	2	4	1	1	3	2	3	3	1	3	1	3	3	1	4	3	3	1	3	1	1	3	4	2	3	2	2	2	3	2	24,259
1	2200	1	4	4	4	3	1	4	1	3	2	3	1	3	3	1	2	3	3	3	4	3	1	1	2	3	3	3	3	3	2	1	2	1	3	3	1	2	2	3	2	24,275
1	2300	1	1	3	4	2	3	2	3	1	1	3	2	1	1	3	3	4	4	1	3	3	3	4	3	3	3	1	3	2	4	3	1	3	1	2	2	3	2	3	2	24,291
1	2400	1	1	3	1	1	4	3	1	4	2	3	3	3	4	3	3	3	3	4	3	2	1	1	3	3	2	3	3	1	2	3	1	2	3	1	4	2	3	2	2	24,307
1	2500	3	4	1	3	1	1	2	2	3	1	3	3	1	4	1	1	3	2	4	2	3	1	4	3	3	3	3	3	4	2	3	3	2	3	1	3	3	2	1	2	24,318

Table 6-6 Bees Algorithm generated routing and costs related to sequences in Table 6-4

Quality (q)	Distance (km)	Remanufacturing Method (1=Reuse, 2=Reincarnate, 3=Recycle, 4=Disposal)																																									Cost (£)
1	2600	1	4	1	3	2	3	3	3	4	3	4	2	4	1	3	1	1	3	3	3	2	3	1	1	4	1	3	3	2	3	3	3	1	2	3	1	2	2	3	2	24,339
1	2700	1	4	3	4	3	1	3	1	3	1	2	3	2	2	3	1	1	3	3	1	3	3	4	3	1	3	2	4	2	3	3	4	3	2	3	1	3	1	2	2	24,350
1	2800	3	4	1	1	3	3	3	3	3	2	3	4	1	3	4	1	4	1	3	2	1	3	4	2	3	1	1	1	2	3	2	3	3	1	3	3	2	3	2	2	24,371
1	2900	1	3	3	3	2	1	4	3	4	1	3	3	4	3	1	2	2	1	1	2	3	4	2	3	1	3	3	3	1	3	3	4	2	3	3	1	3	2	1	2	24,382
1	3000	1	4	1	3	4	3	1	4	4	2	3	3	3	1	3	3	3	1	3	3	2	1	1	4	3	3	1	2	3	3	3	1	3	2	2	2	1	2	3	2	24,402
1	3100	3	3	1	4	1	3	1	3	1	2	1	3	4	3	1	2	3	4	2	1	3	2	4	2	3	3	1	3	3	3	3	4	3	2	3	1	3	1	2	2	24,414
1	3200	3	4	1	3	1	1	2	2	3	1	3	2	3	3	3	3	3	1	4	3	1	1	4	2	4	2	3	3	1	3	3	3	4	2	3	1	3	2	1	2	24,430
1	3300	3	1	3	1	4	4	3	4	1	3	3	1	3	1	4	2	2	3	3	3	1	3	1	3	3	2	3	1	3	3	2	2	1	1	3	4	2	3	2	2	24,450
1	3400	1	4	1	3	1	3	3	3	4	1	3	1	1	3	4	3	2	1	3	2	1	2	3	2	3	4	2	3	3	3	3	4	3	1	3	1	2	3	2	2	24,462
1	3500	3	3	3	1	4	1	3	2	4	2	1	4	3	1	2	2	3	3	1	1	3	3	3	1	4	2	1	3	3	3	4	3	3	1	2	3	3	1	2	2	24,477
1	3600	1	4	2	1	1	4	3	1	3	1	3	3	4	1	3	1	3	4	2	4	1	3	3	3	3	3	1	3	3	3	2	2	2	3	3	1	2	3	2	2	24,498
1	3700	3	1	1	3	1	1	4	2	3	2	3	3	3	4	1	3	1	2	1	2	4	3	3	3	1	3	4	2	3	3	3	3	1	4	3	1	2	3	2	2	24,509
1	3800	1	3	3	1	3	4	4	3	3	1	2	1	1	2	2	3	1	1	2	3	1	4	2	3	3	3	3	4	3	3	3	3	4	2	3	1	3	1	2	2	24,525
1	3900	1	4	3	1	1	1	1	4	2	3	1	3	2	3	3	4	2	4	1	3	3	3	3	3	3	3	3	4	3	2	2	3	1	2	3	1	3	1	2	2	24,545
1	4000	1	1	4	2	1	3	4	1	3	1	3	2	3	3	3	1	2	3	4	2	3	3	2	3	3	3	1	3	1	3	1	4	1	4	3	3	2	3	2	2	24,557
1	4100	3	3	1	3	3	4	4	1	1	4	1	4	1	2	3	3	1	3	2	1	2	3	3	1	2	2	3	3	3	3	3	4	3	2	3	1	3	1	2	2	24,577
1	4200	1	1	4	1	3	4	1	3	1	3	3	3	1	4	2	4	3	2	3	2	3	1	3	4	3	3	3	1	2	2	3	3	1	3	1	3	2	3	2	2	24,593
1	4300	3	1	1	4	2	3	1	4	3	3	1	4	1	2	3	3	1	3	4	1	3	3	1	2	3	3	2	4	3	3	3	1	2	3	1	2	3	3	2	2	24,609
1	4400	3	4	1	4	3	1	4	3	2	3	2	1	3	1	1	3	3	1	2	3	2	1	3	1	3	3	3	4	2	3	4	2	3	3	3	1	3	2	1	2	24,621
1	4500	3	3	1	4	1	3	2	4	3	1	4	3	1	1	3	3	2	1	1	3	1	2	4	3	3	3	3	4	2	3	2	2	3	3	3	1	3	2	1	2	24,641
1	4600	1	3	4	4	1	3	3	3	2	3	1	1	3	3	3	2	1	3	4	3	4	1	1	3	3	1	1	4	3	3	3	2	2	2	2	1	3	3	2	2	24,657
1	4700	1	4	3	3	1	1	1	4	4	2	2	3	3	4	2	3	1	1	3	1	3	3	3	3	4	1	3	1	2	1	3	3	2	3	3	2	3	3	2	2	24,673
1	4800	3	3	3	1	3	4	1	1	4	1	3	3	2	2	4	1	1	3	2	2	1	1	4	2	3	3	3	3	3	4	3	2	3	1	3	3	1	3	2	2	24,684
1	4900	3	4	3	1	3	4	2	4	3	2	3	1	3	3	1	3	1	1	3	3	3	3	1	2	3	1	4	2	2	3	1	3	4	1	3	1	2	3	2	2	24,704
1	5000	1	4	3	2	1	3	3	4	3	3	4	1	3	2	3	3	1	1	3	3	2	2	1	4	2	1	3	3	1	3	3	1	3	1	4	2	3	3	2	2	24,716

The DMM was run varying quality by 0.1units from 0-1.0 and distance by 100km from 0-5000km to evaluate the relationships that would determine whether the product should be recovered for remanufacturing or not. Working with a breakeven of £26,600, Figure 6-4 displays the results of varying quality and distance between the product and remanufacturing facility on the cost to complete the remanufacturing function, CRF.

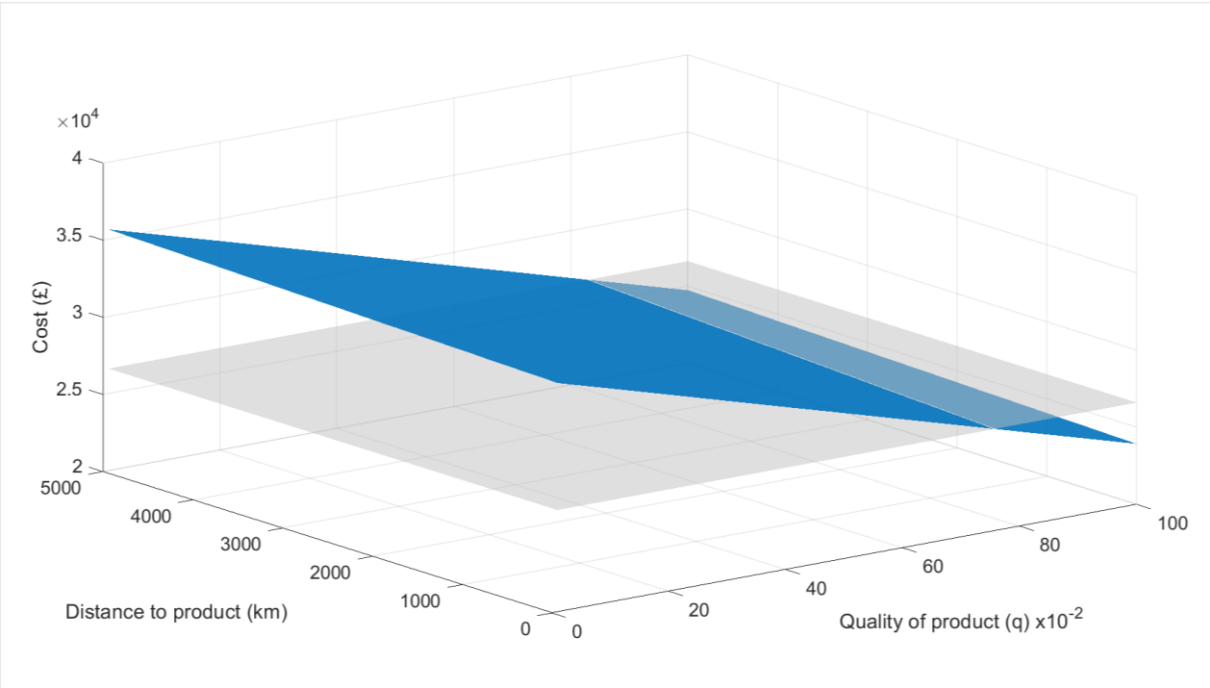

Figure 6-4 Results of DMM

Using this set of raw data there appears to be little opportunity to recover and make profit out of the remanufacturing of this product, identified as the area below the grey breakeven plane. At $q \leq 0.7$ the DT would suggest that the product was not worth recovering and the user should look to find an alternative EoL solution for it. At $q > 0.8$ there could well be opportunity to generate a profit and fulfil a customer order. At $q = 0.8$ the influence of distance is seen with those products closer to the facility profitable, in contrast to those located further away.

As the raw data was generated from a multitude of sources, there may be a case for caution over the exact resultant values, however, what has been demonstrates is that the model can be run in the DT to provide a numerical assessment of the potential profits obtainable from a product in MoL using the DT as the conduit that will enable a data-drive decision by the remanufacturers as to whether or not a product should be recovered, and how best it may be processed.

6.4 Discussion

The output of the DMM provides evidence that a DT can deliver valuable information for remanufacturing businesses. It offers an automated assessment of a products potential to generate revenue assuming the product is in demand. For a fully flexible, highly automated disassembly and re-build process the BA provides a solution that can be used to drive the remanufacturing process plan as well as enabling accurate forecasting to feed forward replacement parts purchasing and reusable component or remanufactured product sales.

The implementation of the directional change penalty matrix to support a more human manageable process to match the case study inputs did offer a slightly more logical disassembly process when discussed with skilled operators but ultimately, this element needs more consideration and could be an interesting progression of this work. Should this model be applied to other applications, more emphasis needs to be placed on this element of the remanufacturing process and the inputs available from the process DT. In this work only the inputs from the product DT were truly considered.

Whilst a thorough sensitivity analysis is recognised as being critical to the task of assessing the robustness of the results, and the impact that different variables have on the output, one has not been conducted as the data that is fed into the model is largely constructed (actual data could

not be sourced). As can be seen from Figure 6-4, the change in product quality, has a significant impact on the cost of recovery as the majority of the optimisation equations include it.

The environmental and social elements of the model have not been tested as part of this research as their similarity to the economic element meant doing so would add little value. The BA has already been proven to solve multi-objective optimisation problems (Pham and Ghanbarzadeh, 2007) and could be used to resolve the complete model. Raw data for the environmental and social elements could also be difficult to capture without the comprehensive engagement of a remanufacturing business. But even at this stage limitations of this numerical assessment method can be identified. The remanufacturers desire or preference to process one product over another and balancing the incoming product requirements with the available capacity of the facility etc. are examples. Further research is needed to thoroughly understand these, and others, within a real recovery decision-making process.

6.5 Summary

This chapter has documented the realisation of the DT sub-element, the DMM, as a continuation of the requirements identified in Chapter 5. The inputs and outputs to the DMM along with the assumptions and relationships have been defined. From this, a model structure is proposed that utilises three of the nine CE-I4.0 methodologies, reuse, remanufacture and recycle. The fourth route available is disposal. The mathematical model brings the research full circle. Based on the 3 pillars of the CE as discussed in Chapter 2, the model offers a numerical assessment of the product and EoL options. In order to test the model, the economic pillar was used and a case study formed. Targeting the lowest incurred costs, the disassembly sequence and component routing was found using the Bess Algorithm implemented in MATLAB. This enables near real-time data-driven decisions to be made for a product approaching EoL that is

still in-use and emitting sensor readings. Combined with the RUL calculations, this information can give remanufacturing businesses foresight into the current quality of the product and its degradation characteristics and remanufacturing potential.

7 CONCLUSION

Chapters 2-4 are copies of published or submitted journal articles so have their own dedicated conclusions found in sections 2.7, 3.8 and 4.7 respectively. The main findings from all chapters have been combined in this final conclusion along with a summary of contributions, further work and closing remarks.

To appreciate previously conducted relevant work, the first part of this thesis offers an overview of smart remanufacturing and the potential for incorporating Industry 4.0 (I4.0) in this sector. Based on the analysis that followed, two overriding themes were identified. The first was that data-driven smart recovery of end-of-life (EoL) products can reduce uncertainties and the burden of subjective, often late in the process, decision-making. The second was that connectivity between customers, suppliers and service providers made possible by I4.0 technologies will change business models by providing early visibility of product status and availability, whist automating the evaluation of risks, benefits, and opportunities.

Products need to be considered for remanufacturing to support the move towards a circular economy (CE). However, products of the same type may have experienced very different in-use life phases and are likely to require different EoL processes. High-value products often have integrated sensors and electronics that can be used to capture in-use data, generally installed for operational or servicing purposes and these could be harnessed for EoL decision-making. A product digital twin (DT) could be the conduit between understanding the current status of the product, and its potential future state using simulations, algorithms, and numerical modelling. This work is the first of its kind to research the requirements of integrating a DT as a solution to enhance product EoL decision-making for remanufacturing to support the CE.

Existing platforms and off-the-shelf components can be used for laboratory based IoT experiments. True real-time connectivity between real and digital products is limited but near real-time is already possible as demonstrated in Chapter 5. Performing predictions for metrics relevant to remanufacturing such as the remaining useful life of a product has been made possible by the developments in sophisticated mathematical modelling processes. In this research MATLAB's deep neural network example was used but the model had to be pre-trained, otherwise the time required to obtain a result exceeded the frequency of evaluation causing the system to crash. It is therefore necessary to balance the time it takes to perform the calculations with the frequency of data extraction and data-user requirements.

There is a need to standardise the architecture relating to smart remanufacturing linking software packages to support faster, reliable processing of through life engineering information, and DTs appear to offer a solution. However, there are several significant challenges to exploiting them for remanufacturing. Both the concept and the technologies involved in DTs are still emerging and lack maturity. Additionally, the DT prototype presented in Chapter 5 utilises I4.0 technology and does have all the elements of a DT as defined by Grieves (2014) but it is not yet 'smart'. What is missing is its ability to initiate and negotiate actions.

There is little research that considers the DT across the entire life cycle of a product. The layers of integration, the potential multiple users, different operating environments, and the need to ensure security, makes the systems complex. Erroneous inbound data and difficulties in mapping scale and units of measurement could escalate into poor outbound predictions, eroding confidence. These issues seem small when compared to the barriers that pertain to intellectual property rights and data management along the supply chain. One of the main challenge to DTs being utilised for remanufacturing purposes is access to BoL and MoL data. Making data a commodity that forms part of a product transaction could offer a solution.

In terms of limitations, what needs to be recognised is that this work has been focused on DTs specifically for remanufacturing and there may well be other requirements and functions, perhaps even contradicting ones, that would benefit other stakeholders and that may be needed to bind the workings of the DT together. It has also only considered high-value low-volume assets, and there could be CE benefits associated with lower-value, mass manufactured product DTs that have not been explored. If the DT is to exist throughout the product's life it needs to add value from design, full circle back to EoL design for second life with functionality scaled accordingly.

7.1 Contributions

All research objectives have been addressed and the key contributions of this work include:

- A systematic study of smart remanufacturing for the CE generating a research framework and agenda that can be exploited by others, achieving objectives 1 and 2.
- Clarification of the extent to which I4.0 technologies are being applied in remanufacturing before defining gaps and opportunities, achieving objective 3.
- Offering the first formalised mapping of remanufacturing sector requirements to emerging DT functionality to develop a UML model for a generic asset. Using I4.0 technologies to build a DT to demonstrate connectivity for product through-life information visibility and decision-making, applying sequence-to-sequence regression and deep learning to predict remaining useful life to drive product recovery strategies before structuring a module using the information available in a product DT to enable a data-driven evaluation of options for end-of-life recovery services optimising financial, environmental, and social benefits using the Bees Algorithm, achieving objective 4.

7.2 Further Work

Identifying opportunities for further work was a foundation output of chapters 2-4. Details are documented in sections 2.6.2, 3.8 and 4.7. In summary, there are many avenues to pursue in this field as research is in its infancy. The need to, develop a strategic time-based roadmap for remanufacturing business to adopt I4.0 concepts, and critique state-of-the-art in design for remanufacturing, emerged from chapter 2. Secondly, having identified the functional requirements for DTs in high-value asset remanufacturing in chapter 4, what is yet to be explored is the depths of data and frequency of sampling and feedback required by a DT to be sufficiently timely for remanufacturers. Thirdly, having used only engines as case studies in this research, the applicability of this approach across a broader spectrum of high-value entities could be considered.

The idea that a DT could be made 'smart' prompts the questions, what would a smart DT do? How would it interact with the real twin if it is there primarily to reflect it, not initiate action? How would this benefit product life extension strategies? Then, if the focus is on extending life, how is this remanufacturing focused DT enhanced to consider the needs of the other stakeholders or life stages? And finally, if the aim of implementing DTs for remanufacturing is to reduce resource consumption, a life-cycle assessment needs to be done on the DT itself. This will be required to ensure the benefits from increasing the circularity of materials based on the information extracted for the DT, are not eclipsed by the computational costs associated with a second digital entity that spends most of its life calculating the potential outputs of scenarios, the vast majority of which will never be realised.

7.3 Closing Remarks

This work is a conceptual melting pot of nascent technologies and opportunities, made possible by digitalisation, and driven by resource conservation. Remanufacturing is perceived as the most desirable innovation strategy to slow resource consumption yet there is little research being conducted in this field. The industry remains volatile, technologically light, and highly dependent on semi-skilled manual labour. As the manufacturing sector shows signs of exploiting emerging technologies associated with the 4th industrial revolution, remanufacturing lingers in the 2nd cautiously looking to adopt methods used by others, to leapfrog the 3rd and forge their own sustainable future, taking advantage of the blank canvas that is Remanufacturing 4.0.

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Appendices

APPENDIX A – NODERED CODE (CLIENT SIDE)

Contained in this appendix is the Node-RED code running on the Raspberry Pi Zero W that mimics the activity of the case study entity (flows shown in Figure 7-1 and Figure 7-2).

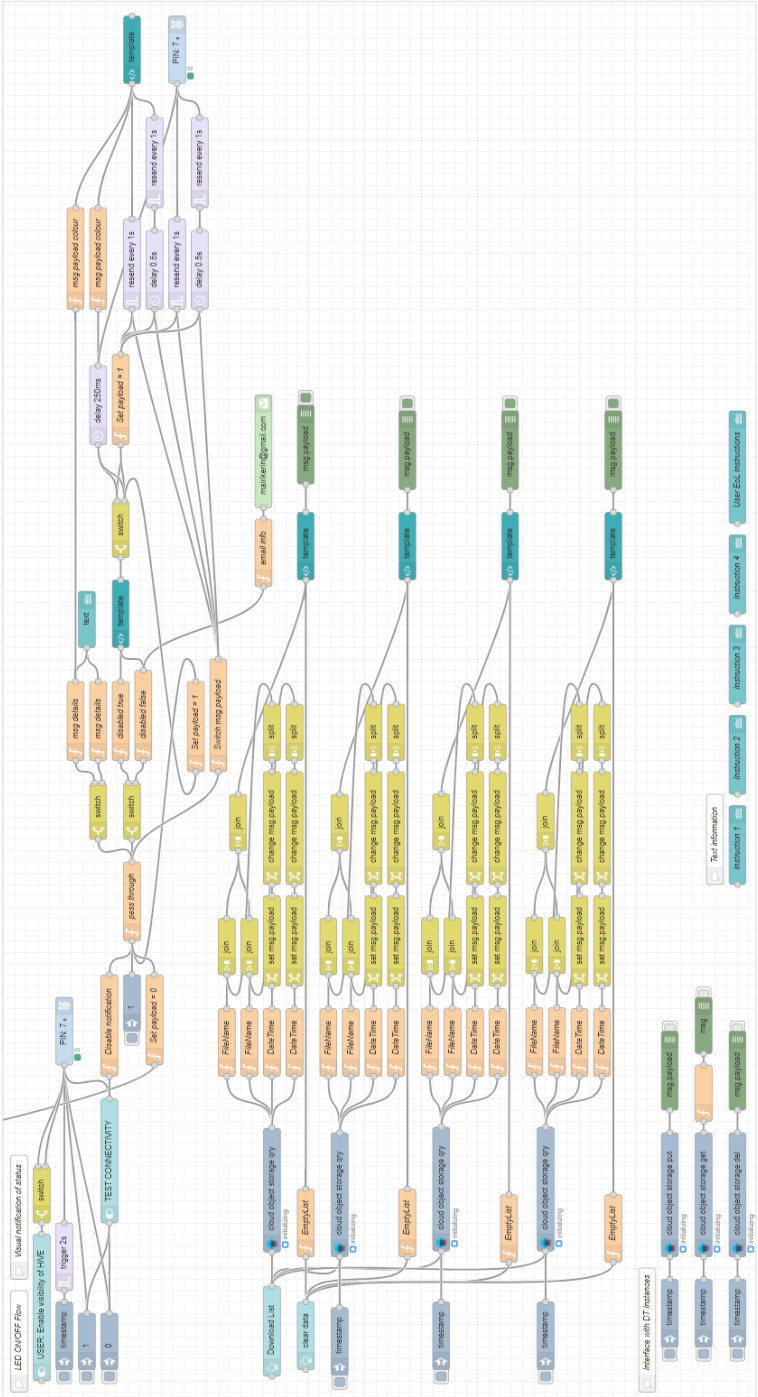

Figure 7-1 The Node-RED flow for Appendix A code (1/2)

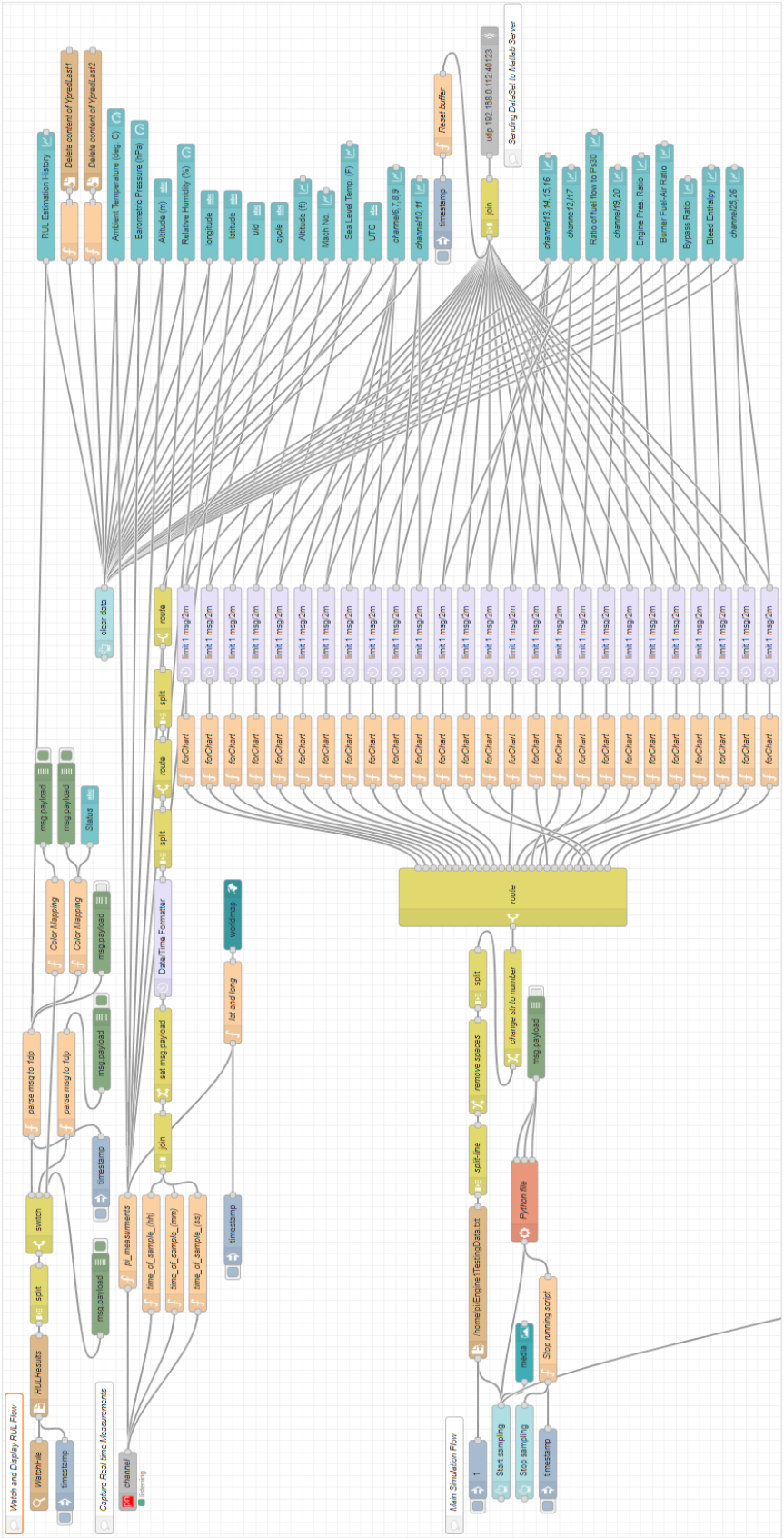

Figure 7-2 The Node-RED flow for Appendix A code (2/2)

‘Watch and Display RUL Flow’ Code

This flow watches a file for updates. When there is a change to the content the flow updates the messages presented in the “Owner Interface” and “EoL Fwd Planning” tabs that relate to the status of the entity. File addresses, personal email addresses, API, subscribe, and publish keys will be removed and replaced with “---_FILE_PATH---”, “---E-MAIL---”, “---API_KEY---”, “---Sub_KEY---” and “---Pub_KEY---” respectively, for security reasons.


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[{"id":"8cc7181.74996e8","type":"inject","z":"30c0838d.13792c"
,"name":"","topic":"","payload":"","payloadType":"date","repea
t":"","crontab":"","once":false,"onceDelay":0.1,"x":120,"y":14
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":"file
in","z":"30c0838d.13792c","name":"RULResults","filename":"/hom
e/pi/gps/---FILE_PATH---
/AllYPredLasts.txt","format":"utf8","chunk":false,"sendError":
false,"encoding":"none","x":290,"y":96,"wires":[["dd709444.d29
1b8"]]},{"id":"a02f404c.e558e","type":"watch","z":"30c0838d.13
792c","name":"WatchFile","files":"/home/pi/gps/---FILE_PATH---
/AllYPredLasts.txt","recursive":"","x":120,"y":96,"wires":[["7
d6169cd.a2c708"]]},{"id":"4e3ffdaa.0e0e44","type":"comment","z
":"30c0838d.13792c","name":"Watch and Display RUL
Flow","info":"","x":140,"y":53,"wires":[]},{"id":"2f9a8dd5.a53
ee2","type":"function","z":"30c0838d.13792c","name":"Color
Mapping","func":"\nif (msg.payload>160) {\n    msg.payload =
\"STATUS: GOOD\"\n    msg.color = \"green\"; }\n    \n
\nelse if (msg.payload<135) { \n    msg.payload =\"STATUS:
FAILED\"\n    msg.color = \"red\"; }\n  \n    \nelse {
msg.payload =\"STATUS: CAUTION\"\n    msg.color = \"orange\";
}\n\nreturn
msg;","outputs":1,"noerr":0,"x":1060,"y":163,"wires":[["bad3af
d.1e80b5","2d7dc32.d78a43c"]]},{"id":"4f860277.19e90c","type":
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"onceDelay":0.1,"x":720,"y":240,"wires":[["54693471.1ca16c"]]}
,{"id":"f0db3875.3f49b8","type":"debug","z":"30c0838d.13792c",
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tatus":false,"complete":"false","x":1050,"y":200,"wires":[]},{
"id":"54693471.1ca16c","type":"function","z":"30c0838d.13792c"
,"name":"parse msg to 1dp","func":"msg.payload =
Number(msg.payload);\nmsg.payload =
parseFloat(msg.payload.toFixed(1))\n\nreturn
msg;","outputs":1,"noerr":0,"x":790,"y":83,"wires":[["1747563.
d1ad1aa","2f9a8dd5.a53ee2","f0db3875.3f49b8"]]},{"id":"dd70944
```

4.d291b8","type":"split","z":"30c0838d.13792c","name":"","splt
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92c","name":"","property":"parts.index","propertyType":"msg","
rules":[{"t":"eq","v":"0","vt":"str"},{"t":"eq","v":"1","vt":"
str"},{"t":"eq","v":"2","vt":"str"}],"checkall":"true","repair
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s":false,"complete":"false","x":1050,"y":240,"wires":[]},{"id"
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false,"complete":"false","x":470,"y":240,"wires":[]},{"id":"5d
fb7156.ab1ea","type":"function","z":"30c0838d.13792c","name":"
parse msg to 1dp","func":"msg.payload =
Number(msg.payload);\n\n\nreturn
msg;","outputs":1,"noerr":0,"x":790,"y":143,"wires":[["8226a32
e.9a3d7"]]},{"id":"9e4ae582.0a6e88","type":"function","z":"30c
0838d.13792c","name":"Color Mapping","func":"\nif
(msg.payload=\"In_Use\") {\n   msg.payload = \"STATUS:
GOOD\"\n   msg.color = \"green\"; }\n   \n   \nif
(msg.payload=\"Consider_Reman\") { \n   msg.payload
=\"STATUS: CAUTION\"\n   msg.color = \"red\"; }\n \n\nreturn
msg;","outputs":1,"noerr":0,"x":1060,"y":123,"wires":[["4f06fb
16.5e5be4"]]},{"id":"4f06fb16.5e5be4","type":"debug","z":"30c0
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lse,"tostatus":false,"complete":"false","x":1270,"y":143,"wire
s":[]},{"id":"2d7dc32.d78a43c","type":"ui_text","z":"30c0838d.
13792c","group":"260f6cc7.e30754","order":4,"width":6,"height"
:2,"name":"Status","label":"","format":" {{msg.payload}} ","layout":"row-
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type":"ui_group","z":"","name":"Engine
Details","tab":"aa362ab0.4c6808","disp":true,"width":12,"colla
pse":false},{"id":"aa362ab0.4c6808","type":"ui_tab","z":"","na
me":"EoL Fwd
Planning","icon":"dashboard","disabled":false,"hidden":false}]

‘Capture Real-time Measurements’ and ‘Main Simulation Flow’ Code

There are two main flows in this section. The first listens to a PubNub channel where the sensor readings for real-time measurement of local ambient temperature, humidity, barometric pressure, latitude, longitude and altitude are published. The measurements are captured and combined with the data from Lau (2017) before being formatted, released, transmitted on UDP and used to populate the graphical user interface. File addresses, personal email addresses, API, subscribe, and publish keys will be removed and replaced with “---_FILE_PATH---”, “---E-MAIL---”, “---API_KEY---”, “---Sub_KEY---” and “---Pub_KEY---” respectively, for security reasons.


```
[{"id":"fb9fb866.958048","type":"pubnub
in","z":"30c0838d.13792c","keys":"4a935381.85dabc","channel":"
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6d0ca.82622","54b974b9.cc0e3c","2446db6a.113ce4"]]},{"id":"535
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"","group":"6834e5af.28759c","order":2,"width":"0","height":"0
","passthru":false,"label":"  Start sampling","tooltip":"click
to start","color":"","bgcolor":"green","icon":"fa-tachometer
fa-
2x","payload":"1","payloadType":"num","topic":"","x":160,"y":1
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a","5817e703.adef18"]]},{"id":"6abc3e73.12f9","type":"exec","z
":"30c0838d.13792c","command":"sudo python3 /home/pi/gps/---
FILE_PATH---
/gps_simpletest3.py","addpay":true,"append":"","useSpawn":"fal
se","timer":"60","oldrc":false,"name":"Python
file","x":590,"y":1316,"wires":[["d464497f.f86488"],["d464497f
.f86488"],["d464497f.f86488"]]},{"id":"7e9e3ccf.2004c4","type"
:"inject","z":"30c0838d.13792c","name":"","topic":"","payload"
:"1","payloadType":"num","repeat":"","crontab":"","once":false
,"onceDelay":0.1,"x":130,"y":1236,"wires":[["f874c645.7e5798"]
]},{"id":"2a016ffa.5474f","type":"split","z":"30c0838d.13792c"
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:[["d745f210.b15e1"]]},{"id":"fe48240f.adbeb8","type":"switch"
,"z":"30c0838d.13792c","name":"route","property":"parts.index"
,"propertyType":"msg","rules":[{"t":"eq","v":"0","vt":"num"},{
```

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q","v":"7","vt":"str"},{"t":"eq","v":"8","vt":"str"},{"t":"eq"
,"v":"9","vt":"str"},{"t":"eq","v":"10","vt":"str"},{"t":"eq",
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f4"],["a4ca4492.615708"],["3a99f217.10b72e"],["8d0b9be4.a75748
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,["910caa79.07d718"],["5a8f3af4.eec784"],["16aeca1a.8e7806"],[
"f4881134.7b7c5"],["531ea1e0.7cbfc"],["98545086.596b4"],["c18b
d6d7.46ccb8"],["6de59da6.9933d4"],["636d811a.9224e"],["997ec61
6.34ca68"],["c1821144.45cee"],["3446df47.7c9d5"]]},{"id":"39fb
b209.bb9fee","type":"change","z":"30c0838d.13792c","name":"cha
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number","rules":[{"t":"set","p":"payload","pt":"msg","to":"$nu
mber(msg.payload)\t","tot":"jsonata"}],"action":"","property":
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e48240f.adbeb8"]]},{"id":"55c2de6b.a2fa2","type":"split","z":"
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":false,"addname":"","x":970,"y":1236,"wires":[["39fbb209.bb9f
ee"]]},{"id":"d745f210.b15e1","type":"change","z":"30c0838d.13
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","from":"","to":"","reg":false,"x":820,"y":1236,"wires":[["55
c2de6b.a2fa2"]]},{"id":"60ecceb.ae6b13","type":"ui_text","z":"
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,"height":1,"name":"uid","label":"UID","format":"{{msg.payload
}}","layout":"row-
center","x":2250,"y":856,"wires":[]},{"id":"13ff10ac.430d5f","
type":"ui_text","z":"30c0838d.13792c","group":"260f6cc7.e30754
","order":7,"width":6,"height":2,"name":"cycle","label":"Cycle
","format":"{{msg.payload}}","layout":"row-
center","x":2250,"y":896,"wires":[]},{"id":"dbfafc78.4e714","t
ype":"ui_chart","z":"30c0838d.13792c","name":"","group":"1ab15
73d.485419","order":4,"width":0,"height":0,"label":"Altitude
(ft)","chartType":"line","legend":"false","xformat":"HH:mm:ss"

,"interpolate":"step","nodata":"Please
wait...","dot":false,"ymin":"0","ymax":"50","removeOlder":"10"
,"removeOlderPoints":"","removeOlderUnit":"60","cutout":0,"use
OneColor":false,"useUTC":false,"colors":["#1f77b4","#aec7e8","
#ff7f0e","#2ca02c","#98df8a","#d62728","#ff9896","#9467bd","#c
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e6.69175"]]},{"id":"e30edee6.69175","type":"delay","z":"30c083
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nute","randomFirst":"1","randomLast":"5","randomUnits":"second
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cb01bf.326a3e8"]]},{"id":"5669634a.01758c","type":"ui_chart","
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No.","chartType":"line","legend":"false","xformat":"HH:mm:ss",
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wait...","dot":false,"ymin":"0","ymax":"1","removeOlder":"10",
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neColor":false,"useUTC":false,"colors":["#1f77b4","#aec7e8","#
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b0d5"],"useOldStyle":false,"outputs":1,"x":2260,"y":976,"wires
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emoveOlderPoints":"","removeOlderUnit":"60","cutout":0,"useOne
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d5"],"useOldStyle":false,"outputs":1,"x":2300,"y":1016,"wires"
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(R)","chartType":"line","legend":"true","xformat":"HH:mm:ss","
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wait...","dot":false,"ymin":"","ymax":"","removeOlder":"10","r
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:[[]]},{"id":"c003b21b.cf43e","type":"function","z":"30c0838d.
13792c","name":"forChart","func":"msg.parts.index =2;\nreturn
msg;","outputs":1,"noerr":0,"x":1360,"y":776,"wires":[["d5367e
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ecb01bf.326a3e8"]]},{"id":"95f93407.2b8c58","type":"function",
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nute","randomFirst":"1","randomLast":"5","randomUnits":"second
s","drop":false,"x":1560,"y":816,"wires":[["dbfafc78.4e714","e
cb01bf.326a3e8"]]},{"id":"1cd60998.dd30b6","type":"function","
z":"30c0838d.13792c","name":"forChart","func":"msg.parts.index
=4;\nreturn
msg;","outputs":1,"noerr":0,"x":1360,"y":856,"wires":[["7d93df
8d.fdf63"]]},{"id":"7d93df8d.fdf63","type":"delay","z":"30c083
8d.13792c","name":"","pauseType":"rate","timeout":"10","timeou
tUnits":"seconds","rate":"1","nbRateUnits":"2","rateUnits":"mi
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ecb01bf.326a3e8"]]},{"id":"547e606d.bd7a6","type":"function","
z":"30c0838d.13792c","name":"forChart","func":"msg.parts.index
=5;\nreturn
msg;","outputs":1,"noerr":0,"x":1360,"y":896,"wires":[["ee4c51
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tUnits":"seconds","rate":"1","nbRateUnits":"2","rateUnits":"mi
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cb01bf.326a3e8"]]},{"id":"3efbdbf9.20e434","type":"function","
z":"30c0838d.13792c","name":"forChart","func":"msg.parts.index
=6;\nmsg.topic = 'Temp FanIn';\n\nreturn
[msg];","outputs":1,"noerr":0,"x":1360,"y":936,"wires":[["47d2
f68e.20c8d8"]]},{"id":"976faa6e.e42ca8","type":"function","z":
"30c0838d.13792c","name":"forChart","func":"msg.parts.index
=7;\nmsg.topic = 'Temp LPCOut';\n\nreturn
[msg];","outputs":1,"noerr":0,"x":1360,"y":976,"wires":[["72c9
98d5.700fe8"]]},{"id":"214d3b80.6d6df4","type":"function","z":
"30c0838d.13792c","name":"forChart","func":"msg.parts.index
=8;\nmsg.topic = 'Temp HPCOut';\n\nreturn
[msg];","outputs":1,"noerr":0,"x":1360,"y":1016,"wires":[["b8c
ab362.ee322"]]},{"id":"a4ca4492.615708","type":"function","z":
"30c0838d.13792c","name":"forChart","func":"msg.parts.index
=9;\nmsg.topic = 'Temp LPTOut';\n\nreturn
[msg];","outputs":1,"noerr":0,"x":1360,"y":1056,"wires":[["1e3
e49e4.8c4536"]]},{"id":"47d2f68e.20c8d8","type":"delay","z":"3
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imeoutUnits":"seconds","rate":"1","nbRateUnits":"2","rateUnits
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st":"5","randomUnits":"seconds","drop":false,"x":1560,"y":1056
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rChart","func":"msg.parts.index =15;\nmsg.topic = 'Fan Speed
(actual)';\n\nreturn
[msg];","outputs":1,"noerr":0,"x":1360,"y":1296,"wires":[["c58
f0b73.52f448"]]},{"id":"c58f0b73.52f448","type":"delay","z":"3
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imeoutUnits":"seconds","rate":"1","nbRateUnits":"2","rateUnits
":"minute","randomFirst":"1","randomLast":"5","randomUnits":"s
econds","drop":false,"x":1560,"y":1296,"wires":[["4bda6928.bc4
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ion","z":"30c0838d.13792c","name":"forChart","func":"msg.parts
.index =16;\nmsg.topic = 'Fan Speed (corr.)';\n\nreturn
[msg];","outputs":1,"noerr":0,"x":1360,"y":1336,"wires":[["bbd
bea12.cedab8"]]},{"id":"bbdbea12.cedab8","type":"delay","z":"3
0c0838d.13792c","name":"","pauseType":"rate","timeout":"10","t
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":"minute","randomFirst":"1","randomLast":"5","randomUnits":"s
econds","drop":false,"x":1560,"y":1336,"wires":[["4bda6928.bc4
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hart","z":"30c0838d.13792c","name":"channel13,14,15,16","group
":"c791f4d.414ac08","order":7,"width":"6","height":"6","label"
:"Fan
Speed","chartType":"line","legend":"true","xformat":"HH:mm:ss"
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wait...","dot":false,"ymin":"","ymax":"","removeOlder":"10","r
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tude =
parseFloat(msg.payload.longitude.toFixed(4))\n\nmsg.payload.hu
midity =
parseFloat(msg.payload.humidity.toFixed(1))\nmsg.payload.altit
ude =
parseFloat(msg.payload.altitude.toFixed(1))\nmsg.payload.tempe
rature =
parseFloat(msg.payload.temperature.toFixed(1))\n\nmsg.payload.
temp =
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3b1ca","type":"ui_gauge","z":"30c0838d.13792c","name":"","grou
p":"d597ebc2.b1db58","order":6,"width":0,"height":0,"gtype":"w
ave","title":"Relative Humidity
(%)","label":"%","format":"{{msg.payload.humidity}}","min":0,"
max":"100","colors":["#ca3838","#00c400","#ca3838"],"seg1":"10
","seg2":"90","x":2300,"y":736,"wires":[]},{"id":"b8ba89d9.69c
c58","type":"split","z":"30c0838d.13792c","name":"","splt":"11
","spltType":"len","arraySplt":"11","arraySpltType":"len","str
eam":false,"addname":"","x":1210,"y":696,"wires":[["c9535b0e.9
d6558"]]},{"id":"7732eff6.10ad","type":"split","z":"30c0838d.1
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arraySpltType":"len","stream":false,"addname":"","x":1450,"y":
696,"wires":[["f66c4e6b.5c6a"]]},{"id":"c9535b0e.9d6558","type
":"switch","z":"30c0838d.13792c","name":"route","property":"pa
rts.index","propertyType":"msg","rules":[{"t":"eq","v":"1","vt
":"num"}],"checkall":"true","repair":false,"outputs":1,"x":133
0,"y":696,"wires":[["7732eff6.10ad"]]},{"id":"f66c4e6b.5c6a","
type":"switch","z":"30c0838d.13792c","name":"route","property"
:"parts.index","propertyType":"msg","rules":[{"t":"eq","v":"0"
,"vt":"num"}],"checkall":"true","repair":false,"outputs":1,"x"
:1590,"y":696,"wires":[["13aee0ae.987abf"]]},{"id":"25eb3e0.29
df5c2","type":"inject","z":"30c0838d.13792c","name":"","topic"
:"","payload":"","payloadType":"date","repeat":"","crontab":""
,"once":false,"onceDelay":0.1,"x":140,"y":1356,"wires":[["bf8f
1099.10644"]]},{"id":"bf8f1099.10644","type":"function","z":"3
0c0838d.13792c","name":"Stop running script","func":"delete
msg.payload;\nmsg.kill=\"SIGKILL\";\nreturn
msg;","outputs":1,"noerr":0,"x":370,"y":1356,"wires":[["6abc3e
73.12f9"]]},{"id":"24943f02.2bc32","type":"ui_button","z":"30c
0838d.13792c","name":"","group":"6834e5af.28759c","order":3,"w
idth":"0","height":"0","passthru":false,"label":" Stop
sampling","tooltip":"click to
start","color":"","bgcolor":"orange","icon":"fa-tachometer fa-
2x","payload":"1","payloadType":"num","topic":"","x":160,"y":1
316,"wires":[["bf8f1099.10644"]]},{"id":"11a3a42f.92acbc","typ
e":"moment","z":"30c0838d.13792c","name":"","topic":"","input"
:"","inputType":"msg","inTz":"Europe/London","adjAmount":0,"ad
jType":"days","adjDir":"add","format":"","locale":"en_GB","out

put":"","outputType":"msg","outTz":"Europe/London","x":1040,"y
":696,"wires":[["b8ba89d9.69cc58"]]},{"id":"ecb01bf.326a3e8","
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build":"string","property":"payload","propertyType":"msg","key
":"topic","joiner":"
","joinerType":"str","accumulate":false,"timeout":"","count":"
26","reduceRight":false,"reduceExp":"","reduceInit":"","reduce
InitType":"num","reduceFixup":"","x":2290,"y":1256,"wires":[["
bae271fa.51fdc"]]},{"id":"f874c645.7e5798","type":"file
in","z":"30c0838d.13792c","name":"","filename":"/home/pi/Engin
e1TestingData.txt","format":"utf8","chunk":false,"sendError":f
alse,"encoding":"none","x":450,"y":1236,"wires":[["2a016ffa.54
74f"]]},{"id":"bae271fa.51fdc","type":"udp
out","z":"30c0838d.13792c","name":"","addr":"192.168.0.112","i
face":"","port":"40123","ipv":"udp4","outport":"40121","base64
":false,"multicast":"broad","x":2490,"y":1256,"wires":[]},{"id
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oup":"260f6cc7.e30754","name":"","width":6,"height":5,"order":
3,"category":"images","file":"RR
Engine.png","layout":"center","showcontrols":true,"loop":true,
"onstart":false,"scope":"local","tooltip":"","x":330,"y":1316,
"wires":[[]]},{"id":"1747563.d1ad1aa","type":"ui_chart","z":"3
0c0838d.13792c","name":"","group":"260f6cc7.e30754","order":5,
"width":6,"height":6,"label":"RUL Estimation
History","chartType":"line","legend":"false","xformat":"HH:mm:
ss","interpolate":"linear","nodata":"Please
wait...","dot":false,"ymin":"","ymax":"","removeOlder":1,"remo
veOlderPoints":"","removeOlderUnit":"3600","cutout":0,"useOneC
olor":false,"useUTC":false,"colors":["#1f77b4","#aec7e8","#ff7
f0e","#2ca02c","#98df8a","#be2323","#ff9896","#9467bd","#c5b0d
5"],"useOldStyle":false,"outputs":1,"x":2310,"y":496,"wires":[
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792c","name":"Capture Real-time
Measurements","info":"","x":150,"y":596,"wires":[]},{"id":"e28
4cca1.3a1cc","type":"comment","z":"30c0838d.13792c","name":"Ma
in Simulation
Flow","info":"","x":120,"y":1196,"wires":[]},{"id":"5afaae6c.a
df65","type":"comment","z":"30c0838d.13792c","name":"Sending
DataSet to Matlab
Server","info":"","x":2500,"y":1296,"wires":[]},{"id":"88a8696
5.9b9328","type":"inject","z":"30c0838d.13792c","name":"","top
ic":"","payload":"","payloadType":"date","repeat":"","crontab"
:"","once":false,"onceDelay":0.1,"x":2280,"y":1176,"wires":[["
71758269.9fab4c"]]},{"id":"71758269.9fab4c","type":"function",
"z":"30c0838d.13792c","name":"Reset
buffer","func":"msg.payload = msg.complete;\nreturn
msg;","outputs":1,"noerr":0,"x":2450,"y":1176,"wires":[["ecb01
bf.326a3e8"]]},{"id":"4dfe96cd.31f388","type":"file","z":"30c0
838d.13792c","name":"Delete content of

YpredLast1","filename":"/home/pi/gps/---FILE_PATH---
/YpredLast1.txt","appendNewline":false,"createDir":false,"over
writeFile":"true","encoding":"none","x":2440,"y":536,"wires":[
[]]},{"id":"f2fd253f.f5d898","type":"function","z":"30c0838d.1
3792c","name":"","func":"msg.payload = \"\";\nreturn
msg;","outputs":1,"noerr":0,"x":2250,"y":536,"wires":[["4dfe96
cd.31f388"]]},{"id":"d0cfe9ad.783ae8","type":"file","z":"30c08
38d.13792c","name":"Delete content of
YpredLast2","filename":"/home/pi/gps/---FILE_PATH---
/YpredLast2.txt","appendNewline":false,"createDir":false,"over
writeFile":"true","encoding":"none","x":2440,"y":576,"wires":[
[]]},{"id":"24bfca12.0e15f6","type":"function","z":"30c0838d.1
3792c","name":"","func":"msg.payload = \"\";\nreturn
msg;","outputs":1,"noerr":0,"x":2250,"y":576,"wires":[["d0cfe9
ad.783ae8"]]},{"id":"d464497f.f86488","type":"debug","z":"30c0
838d.13792c","name":"","active":false,"tosidebar":true,"consol
e":false,"tostatus":false,"complete":"false","x":870,"y":1336,
"wires":[]},{"id":"4a1d9d51.e1bf14","type":"ui_gauge","z":"30c
0838d.13792c","name":"","group":"d597ebc2.b1db58","order":3,"w
idth":0,"height":0,"gtype":"gage","title":"Barometric Pressure
(hPa)","label":"hPa","format":"{{msg.payload.pressure}}","min"
:"900","max":"1100","colors":["#ca3838","#00b500","#ca3838"],"
seg1":"995","seg2":"","x":2320,"y":656,"wires":[]},{"id":"f915
0ea0.e0966","type":"ui_worldmap","z":"30c0838d.13792c","group"
:"f7af5b0f.b49498","order":4,"width":"12","height":"8","name":
"","lat":"52.7","lon":"-1.9","zoom":"6","layer":"OSM
grey","cluster":"","maxage":"","usermenu":"hide","layers":"hid
e","panit":"false","panlock":"false","zoomlock":"false","hider
ightclick":"true","coords":"none","showgrid":"false","path":"/
worldmap","x":1080,"y":816,"wires":[]},{"id":"b2a6826a.1c2fd",
"type":"function","z":"30c0838d.13792c","name":"lat and
long","func":"lat = msg.payload.latitude;\nlon =
msg.payload.longitude;\n\n\nmsg.payload = { \"name\":\"1\",
\"lat\":lat, \"lon\":lon }\nreturn
msg;","outputs":1,"noerr":0,"x":930,"y":816,"wires":[["f9150ea
0.e0966"]]},{"id":"6ddb3933.7f57f8","type":"inject","z":"30c08
38d.13792c","name":"","topic":"","payload":"","payloadType":"d
ate","repeat":"","crontab":"","once":false,"onceDelay":0.1,"x"
:540,"y":816,"wires":[["b2a6826a.1c2fd"]]},{"id":"4a935381.85d
abc","type":"pubnub-keys","z":"","pub_key":"---Pub_KEY---
","sub_key":"---Sub_KEY---
"},{"id":"6834e5af.28759c","type":"ui_group","z":"","name":"De
vice
Management","tab":"e1641989.8d5ae8","disp":true,"width":"6","c
ollapse":false},{"id":"260f6cc7.e30754","type":"ui_group","z":
"","name":"Engine
Details","tab":"aa362ab0.4c6808","disp":true,"width":12,"colla
pse":false},{"id":"1ab1573d.485419","type":"ui_group","z":"","
name":"Operating

Conditions","tab":"1bc05064.5d81b","disp":true,"width":"6","co
llapse":false},{"id":"3d798ff6.0daeb","type":"ui_group","z":""
,"name":"Temperature
(R)","tab":"1bc05064.5d81b","disp":true,"width":"6","collapse"
:false},{"id":"c791f4d.414ac08","type":"ui_group","z":"","name
":"Speed
(rpm)","tab":"1bc05064.5d81b","disp":true,"width":"6","collaps
e":false},{"id":"b145d9b9.178b08","type":"ui_group","z":"","na
me":"Operating
Parameters","tab":"1bc05064.5d81b","disp":true,"width":"6","co
llapse":false},{"id":"8e24d1e9.b49da","type":"ui_group","z":""
,"name":"Pressure
(psai)","tab":"1bc05064.5d81b","disp":true,"width":"6","collap
se":false},{"id":"cbc7f8fa.fbfc48","type":"ui_group","z":"","n
ame":"Current time and
location","tab":"e1641989.8d5ae8","disp":true,"width":"6","col
lapse":false},{"id":"d597ebc2.b1db58","type":"ui_group","z":""
,"name":"Local
Conditions","tab":"e1641989.8d5ae8","disp":true,"width":"6","c
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"","name":"Map","tab":"e1641989.8d5ae8","disp":true,"width":"1
2","collapse":false},{"id":"e1641989.8d5ae8","type":"ui_tab","
z":"","name":"Live
Status","icon":"dashboard","order":1,"disabled":false,"hidden"
:false},{"id":"aa362ab0.4c6808","type":"ui_tab","z":"","name":
"EoL Fwd
Planning","icon":"dashboard","disabled":false,"hidden":false},
{"id":"1bc05064.5d81b","type":"ui_tab","z":"","name":"Engine1"
,"icon":"mi-
fingerprint","order":2,"disabled":false,"hidden":false}]

<u>‘LED ON/OFF Flow’ and ‘Visual Notification of Status’ Code</u>

These flows use the data to turn on/off the LED to indicate different status. It also allows the user interface users to interact and remotely change the state of the LED. Additionally, the flows provide information and structure to the user-interface’s “Owners Interface” and triggers the automatic email function. File addresses, personal email addresses, API, subscribe, and publish keys will be removed and replaced with “---_FILE_PATH---”, “---E-MAIL---”, “---API_KEY---”, “---Sub_KEY---” and “---Pub_KEY---” respectively, for security reasons.

[{"id":"e41969fe.90c478","type":"inject","z":"30c0838d.13792c"
,"name":"","topic":"","payload":"0","payloadType":"num","repea
t":"","crontab":"","once":false,"onceDelay":0.1,"x":110,"y":21
07,"wires":[["f9974514.23e558","e87d8b2d.c272d8"]]},{"id":"6d5
27ce.a890784","type":"inject","z":"30c0838d.13792c","name":"",
"topic":"","payload":"1","payloadType":"num","repeat":"","cron
tab":"","once":false,"onceDelay":0.1,"x":110,"y":2067,"wires":
[["f9974514.23e558","e87d8b2d.c272d8"]]},{"id":"f9974514.23e55
8","type":"rpi-gpio
out","z":"30c0838d.13792c","name":"","pin":"7","set":true,"lev
el":"0","freq":"","out":"out","x":660,"y":2027,"wires":[]},{"i
d":"c48dd4.d1da123","type":"comment","z":"30c0838d.13792c","na
me":"LED ON/OFF
Flow","info":"","x":110,"y":1947,"wires":[]},{"id":"e45a68ad.d
10648","type":"trigger","z":"30c0838d.13792c","op1":"1","op2":
"0","op1type":"str","op2type":"str","duration":"2","extend":fa
lse,"units":"s","reset":"","bytopic":"all","name":"","x":260,"
y":2027,"wires":[["f9974514.23e558"]]},{"id":"457e1c97.1fe954"
,"type":"inject","z":"30c0838d.13792c","name":"","topic":"","p
ayload":"","payloadType":"date","repeat":"","crontab":"","once
":false,"onceDelay":0.1,"x":120,"y":2027,"wires":[["e45a68ad.d
10648"]]},{"id":"e87d8b2d.c272d8","type":"ui_switch","z":"30c0
838d.13792c","name":"","label":"TEST
CONNECTIVITY","tooltip":"Check Yellow
LED","group":"6834e5af.28759c","order":1,"width":"0","height":
"0","passthru":true,"decouple":"false","topic":"","style":"","
onvalue":"true","onvalueType":"bool","onicon":"fa-bolt fa-
2x","oncolor":"green","offvalue":"false","offvalueType":"bool"
,"officon":"fa-power-off fa-
2x","offcolor":"red","x":430,"y":2107,"wires":[["f9974514.23e5
58","15bda982.83ae46"]]},{"id":"31780971.7d7d26","type":"e-
mail","z":"30c0838d.13792c","server":"smtp.gmail.com","port":"
465","secure":true,"tls":false,"name":"---E-MAIL---
","dname":"","x":1720,"y":2340,"wires":[]},{"id":"9809f440.624
838","type":"ui_template","z":"30c0838d.13792c","group":"59901
27.f18c7ec","name":"","order":8,"width":15,"height":2,"format"
:"\n<md-switch ng-model=\"msg.payload\" ng-
change=\"send(msg)\" ng-disabled=\"msg.payload.disabled\">
{{msg.payload.disabled ? 'USER: Enable visibility of HiVE
(Switch currently disabled)': 'USER: Enable visibility of
HiVE'}} </md-switch>\n\n\n<script>\n   (function(scope) {\n
console.log('Position 1');\n   console.dir(scope);\n
console.log(scope.msg);\n
scope.$watch('msg.payload.disabled', function(data) {\n
console.log('Position 2');\n   console.dir(data);\n
});\n
})(scope);\n</script>\n","storeOutMessages":true,"fwdInMessage
s":false,"resendOnRefresh":false,"templateScope":"local","x":1
400,"y":2127,"wires":[["73634099.ccd7b"]]},{"id":"c16711e3.5d0

bc","type":"function","z":"30c0838d.13792c","name":"disabled
true","func":"msg.payload = {\"disabled\":true};\nreturn
msg;","outputs":1,"noerr":0,"x":1210,"y":2127,"wires":[["9809f
440.624838"]]},{"id":"b5cce415.5c0928","type":"function","z":"
30c0838d.13792c","name":"disabled false","func":"msg.payload =
{\"disabled\":false};\nreturn
msg;","outputs":1,"noerr":0,"x":1220,"y":2167,"wires":[["9809f
440.624838","a7a3078d.940658"]]},{"id":"bbf8fe0.fd4e1","type":
"switch","z":"30c0838d.13792c","name":"","property":"payload",
"propertyType":"msg","rules":[{"t":"eq","v":"0","vt":"num"},{"
t":"eq","v":"1","vt":"str"}],"checkall":"true","repair":false,
"outputs":2,"x":1050,"y":2147,"wires":[["c16711e3.5d0bc"],["b5
cce415.5c0928"]]},{"id":"392dad2c.db68b2","type":"trigger","z"
:"30c0838d.13792c","op1":"green","op2":"black","op1type":"str"
,"op2type":"str","duration":"-
1","extend":false,"units":"s","reset":"1","bytopic":"all","nam
e":"","x":2020,"y":2147,"wires":[["fffb862b.e01018"]]},{"id":"
fffb862b.e01018","type":"ui_template","z":"30c0838d.13792c","g
roup":"5990127.f18c7ec","name":"","order":3,"width":3,"height"
:3,"format":"<svg>\n\n<circle cx=\"70\" cy=\"70\" r=\"30\"
style=\"stroke: none; fill: {{msg.payload}};\"/>\n \n</svg>
","storeOutMessages":true,"fwdInMessages":true,"resendOnRefres
h":false,"templateScope":"local","x":2400,"y":2147,"wires":[[]
]},{"id":"deccec4b.8571f","type":"delay","z":"30c0838d.13792c"
,"name":"","pauseType":"delay","timeout":"0.5","timeoutUnits":
"seconds","rate":"1","nbRateUnits":"1","rateUnits":"second","r
andomFirst":"1","randomLast":"5","randomUnits":"seconds","drop
":false,"x":2010,"y":2187,"wires":[["3f6fcc23.f8a844"]]},{"id"
:"3f6fcc23.f8a844","type":"trigger","z":"30c0838d.13792c","op1
":"#F0F0F0","op2":"0","op1type":"str","op2type":"str","duratio
n":"-
1","extend":false,"units":"s","reset":"1","bytopic":"all","nam
e":"","x":2200,"y":2187,"wires":[["fffb862b.e01018"]]},{"id":"
ecb5f5f4.ffea48","type":"function","z":"30c0838d.13792c","name
":"Switch msg.payload","func":"if (msg.payload === 1)
{\nmsg.payload = 0;\n}\n\nelse {\n   \n   msg.payload =
1;\n}\n\nreturn
msg;","outputs":1,"noerr":0,"x":1220,"y":2300,"wires":[["392da
d2c.db68b2","deccec4b.8571f","64c2e263.2d830c","d8ddbd88.9fac8
"]]},{"id":"64c2e263.2d830c","type":"trigger","z":"30c0838d.13
792c","op1":"true","op2":"black","op1type":"bool","op2type":"s
tr","duration":"-
1","extend":false,"units":"s","reset":"1","bytopic":"all","nam
e":"","x":2020,"y":2227,"wires":[["8d0498ff.292d08"]]},{"id":"
d8ddbd88.9fac8","type":"delay","z":"30c0838d.13792c","name":""
,"pauseType":"delay","timeout":"0.5","timeoutUnits":"seconds",
"rate":"1","nbRateUnits":"1","rateUnits":"second","randomFirst
":"1","randomLast":"5","randomUnits":"seconds","drop":false,"x
":2010,"y":2267,"wires":[["32520a17.29d9e6"]]},{"id":"8d0498ff

.292d08","type":"rpi-gpio
out","z":"30c0838d.13792c","name":"","pin":"7","set":true,"lev
el":"0","freq":"","out":"out","x":2400,"y":2227,"wires":[]},{"
id":"32520a17.29d9e6","type":"trigger","z":"30c0838d.13792c","
op1":"false","op2":"0","op1type":"bool","op2type":"str","durat
ion":"-
1","extend":false,"units":"s","reset":"1","bytopic":"all","nam
e":"","x":2200,"y":2267,"wires":[["8d0498ff.292d08"]]},{"id":"
73634099.ccd7b","type":"switch","z":"30c0838d.13792c","name":"
","property":"payload","propertyType":"msg","rules":[{"t":"tru
e"},{"t":"false"}],"checkall":"true","repair":false,"outputs":
2,"x":1550,"y":2127,"wires":[["a9490d6c.e3e2f","b9d0a339.2f678
"],["a9490d6c.e3e2f","b9d0a339.2f678","f907a734.7e1c38"]]},{"i
d":"a9490d6c.e3e2f","type":"function","z":"30c0838d.13792c","n
ame":"Set payload = 1","func":"msg.payload = 1;\nreturn
msg;","outputs":1,"noerr":0,"x":1780,"y":2127,"wires":[["392da
d2c.db68b2","deccec4b.8571f","64c2e263.2d830c","d8ddbd88.9fac8
"]]},{"id":"b9d0a339.2f678","type":"delay","z":"30c0838d.13792
c","name":"","pauseType":"delay","timeout":"250","timeoutUnits
":"milliseconds","rate":"1","nbRateUnits":"1","rateUnits":"sec
ond","randomFirst":"1","randomLast":"5","randomUnits":"seconds
","drop":false,"x":1770,"y":2087,"wires":[["7320b537.9f032c","
8d0498ff.292d08"]]},{"id":"f907a734.7e1c38","type":"function",
"z":"30c0838d.13792c","name":"Set payload =
1","func":"msg.payload = 1;\nreturn
msg;","outputs":1,"noerr":0,"x":1200,"y":2260,"wires":[["16067
5fe.113c1a"]]},{"id":"5578e0f6.aedce","type":"comment","z":"30
c0838d.13792c","name":"Visual notification of
status","info":"","x":330,"y":1947,"wires":[]},{"id":"2ad6f7ff
.8ff768","type":"ui_text","z":"30c0838d.13792c","group":"59901
27.f18c7ec","order":2,"width":15,"height":1,"name":"","label":
"","format":"<font color=
{{msg.color}}>{{msg.payload}}","layout":"row-
center","x":1390,"y":2067,"wires":[]},{"id":"32644f0a.bd901","
type":"switch","z":"30c0838d.13792c","name":"","property":"pay
load","propertyType":"msg","rules":[{"t":"eq","v":"0","vt":"nu
m"},{"t":"eq","v":"1","vt":"num"}],"checkall":"true","repair":
false,"outputs":2,"x":1050,"y":2087,"wires":[["3501b9b2.b262c6
"],["7cc065b.fab279c"]]},{"id":"7cc065b.fab279c","type":"funct
ion","z":"30c0838d.13792c","name":"msg
details","func":"msg.payload = \"ENTITY PERFORMANCE IS REDUCED
- USER SHOULD CONSIDER EoL RECOVERY\";\nmsg.color =
\"green\"\nreturn
msg;","outputs":1,"noerr":0,"x":1210,"y":2087,"wires":[["2ad6f
7ff.8ff768"]]},{"id":"160675fe.113c1a","type":"function","z":"
30c0838d.13792c","name":"pass through","func":"\nreturn
msg;","outputs":1,"noerr":0,"x":890,"y":2147,"wires":[["bbf8fe
0.fd4e1","ecb5f5f4.ffea48","32644f0a.bd901"]]},{"id":"3501b9b2
.b262c6","type":"function","z":"30c0838d.13792c","name":"msg

details","func":"msg.payload = \"ENTITY STILL PERFORMING WELL
- NOT READY FOR EoL RECOVERY\";\nmsg.color = \"red\";\nreturn
msg;","outputs":1,"noerr":0,"x":1210,"y":2047,"wires":[["2ad6f
7ff.8ff768","223088e7.615168"]]},{"id":"7320b537.9f032c","type
":"function","z":"30c0838d.13792c","name":"msg.payload
colour","func":"msg.payload = \"green\";\nreturn
msg;","outputs":1,"noerr":0,"x":2030,"y":2087,"wires":[["fffb8
62b.e01018"]]},{"id":"a7a3078d.940658","type":"function","z":"
30c0838d.13792c","name":"email info","func":"msg.topic =
\"Entity UID ready for EoL management - Requires user
input\";\nmsg.payload = \"This entity should be considered for
EoL management. As owner, the process requires you to accept
this status advice and access the Digital Twin to allert the
EoL systems to be notified. \\n \\n Log in to
http://192.168.0.31:1880/ui/#!/3?socketid=jzR5yCiCTWq1lcIDAAAO
\\n \\n Select 'Owner interface' tab \\n \\n Toggle Switch
USER: Enable visibility of HiVE to ON \\n \\n Light on entity
and interface should turn from flashing to solid \\n \\n EoL
services will be automatically notified\";\nreturn
msg;","outputs":1,"noerr":0,"x":1500,"y":2340,"wires":[["31780
971.7d7d26"]]},{"id":"223088e7.615168","type":"function","z":"
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colour","func":"msg.payload = \"#F0F0F0\";\nreturn
msg;","outputs":1,"noerr":0,"x":2030,"y":2047,"wires":[["fffb8
62b.e01018"]]},{"id":"15bda982.83ae46","type":"function","z":"
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","func":"msg.payload = 0;\nreturn
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3e558"],["f9974514.23e558"]]},{"id":"66e129ea.8c8848","type":"
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Enable visibility of
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color":"","offvalue":"false","offvalueType":"bool","officon":"
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Status","icon":"dashboard","order":1,"disabled":false,"hidden"
:false},{"id":"25d59d53.6f4192","type":"ui_tab","z":"","name":
"Owner
Interface","icon":"dashboard","disabled":false,"hidden":false}
]

Cloud Interface

These flows link to the IBM Cloud allowing the user to download a list of the stored files available in in the different life instances (as-designed, current-state etc.) via the “EoL Fwd Planning” tab on the users interface. File addresses, personal email addresses, API, subscribe, and publish keys will be removed and replaced with “---_FILE_PATH---”, “---E-MAIL---”, “---API_KEY---”, “---Sub_KEY---” and “---Pub_KEY---” respectively, for security reasons.

[{"id":"b23a5d6c.f8c04","type":"ui_button","z":"30c0838d.13792
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List","tooltip":"Pull live list of cloud stored
files","color":"","bgcolor":"","icon":"fa-download
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#mylog {\n   min-height: 95px;\n   min-width:
145px;\n   padding: 0;\n   background-color:
#F0F8FF;\n   white-space: pre;\n   font-size:
15px;\n   text-align: right;\n   }\n</style>\n\n<div
id=\"mylog\" ng-bind=\"msg.payload\"
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>\n \n\n\n","storeOutMessages":true,"fwdInMessages":true,
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13.892428"]]},{"id":"3dfc9d1a.ac33c2","type":"function","z":"3
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msg.payload[0].Key;\n\n\n\nreturn
msg;\n\n","outputs":1,"noerr":0,"x":632,"y":2480,"wires":[["46
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msg;\n\n","outputs":1,"noerr":0,"x":632,"y":2520,"wires":[["dc
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","tot":"str"}],"action":"","property":"","from":"","to":"","r
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95px;\n   min-width: 145px;\n   padding: 0;\n
background-color: #F0F8FF;\n   white-space: pre;\n
font-size: 15px;\n   text-align: right;\n
}\n</style>\n\n<div id=\"mylog\" ng-bind=\"msg.payload\"
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>\n \n\n\n","storeOutMessages":true,"fwdInMessages":true,
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msg.payload = \"\";\nreturn
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msg;\n\n","outputs":1,"noerr":0,"x":632,"y":2700,"wires":[["33
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y":2800,"wires":[]},{"id":"f11bba0c.55d4c8","type":"cos-
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,"reduceFixup":"","x":1023,"y":2860,"wires":[["e0a3aae9.6c24a8
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pre;\n   font-size: 15px;\n   text-align: right;\n
}\n</style>\n\n<div id=\"mylog\" ng-bind=\"msg.payload\"
contenteditable=\"true\">\n   <!-- payload will go here --
>\n \n\n\n","storeOutMessages":true,"fwdInMessages":true,
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33a4","24dd9ada.4f4536"]]},{"id":"50157389.b285ec","type":"inj

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95px;\n   min-width: 145px;\n   padding: 0;\n
background-color: #F0F8FF;\n   white-space: pre;\n
font-size: 15px;\n   text-align: right;\n
}\n</style>\n\n<div id=\"mylog\" ng-bind=\"msg.payload\"
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>\n \n\n\n","storeOutMessages":true,"fwdInMessages":true,
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endpoint":"s3.eu-gb.cloud-object-
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endpoint":"s3.eu-gb.cloud-object-
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Planning","icon":"dashboard","disabled":false,"hidden":false}]

Interface with DT Instances

These flows enable the user to interface with the different DT instances using the “put”, “get” and “delete” nodes. File addresses, personal email addresses, API, subscribe, and publish keys will be removed and replaced with “---_FILE_PATH---”, “---E-MAIL---”, “---API_KEY---”, “---Sub_KEY---” and “---Pub_KEY---” respectively, for security reasons.

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files","color":"","bgcolor":"","icon":"fa-download
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#mylog {\n min-height: 95px;\n min-width:
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15px;\n text-align: right;\n }\n</style>\n\n<div
id=\"mylog\" ng-bind=\"msg.payload\"
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>\n \n\n\n","storeOutMessages":true,"fwdInMessages":true,
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msg.payload[0].Key;\n\n\n\nreturn
msg;\n\n","outputs":1,"noerr":0,"x":632,"y":2480,"wires":[["46
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msg;\n\n","outputs":1,"noerr":0,"x":632,"y":2520,"wires":[["dc
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","tot":"str"}],"action":"","property":"","from":"","to":"","r
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95px;\n   min-width: 145px;\n   padding: 0;\n
background-color: #F0F8FF;\n   white-space: pre;\n
font-size: 15px;\n   text-align: right;\n
}\n</style>\n\n<div id=\"mylog\" ng-bind=\"msg.payload\"

contenteditable=\"true\">\n   <!-- payload will go here --
>\n \n\n\n","storeOutMessages":true,"fwdInMessages":true,
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msg;","outputs":1,"noerr":0,"x":312,"y":2800,"wires":[["cab3df
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msg;\n\n","outputs":1,"noerr":0,"x":632,"y":2700,"wires":[["33
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y":2800,"wires":[]},{"id":"f11bba0c.55d4c8","type":"cos-
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manufactured","maxkeys":50,"cosconfig":"2d70ae41.1ad462","x":3
62,"y":2680,"wires":[["80dd7bab.6976e8","37969251.68ee1e","c22
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]},{"id":"2180c447.226a4c","type":"join","z":"30c0838d.13792c"
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"]]},{"id":"e0a3aae9.6c24a8","type":"ui_template","z":"30c0838
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height: 95px;\n   min-width: 145px;\n   padding:
0;\n   background-color: #F0F8FF;\n   white-space:
pre;\n   font-size: 15px;\n   text-align: right;\n
}\n</style>\n\n<div id=\"mylog\" ng-bind=\"msg.payload\"
contenteditable=\"true\">\n   <!-- payload will go here --
>\n \n\n\n","storeOutMessages":true,"fwdInMessages":true,
"resendOnRefresh":true,"templateScope":"local","x":1512,"y":29
82,"wires":[["62f320af.21429"]]},{"id":"68912b53.fbb974","type
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msg;","outputs":1,"noerr":0,"x":302,"y":2980,"wires":[["e0a3aa
e9.6c24a8"]]},{"id":"73c94ff8.834b4","type":"function","z":"30
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msg.payload[0].Key;\n\n\n\nreturn

msg;\n\n","outputs":1,"noerr":0,"x":633,"y":2840,"wires":[["d5
b1c733.705d78"]]},{"id":"20a8d3d2.987d7c","type":"function","z
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msg.payload[1].Key;\n\nreturn
msg;\n\n","outputs":1,"noerr":0,"x":633,"y":2880,"wires":[["7a
cc1117.c59ce"]]},{"id":"68cf7c49.d233a4","type":"function","z"
:"30c0838d.13792c","name":"DateTime","func":"msg.payload =
msg.payload[0].LastModified;\nreturn
msg;","outputs":1,"noerr":0,"x":632,"y":2920,"wires":[["bd706a
e9.988318"]]},{"id":"24dd9ada.4f4536","type":"function","z":"3
0c0838d.13792c","name":"DateTime","func":"msg.payload =
msg.payload[1].LastModified;\nreturn
msg;","outputs":1,"noerr":0,"x":632,"y":2960,"wires":[["1c2e11
67.8af3af"]]},{"id":"d5b1c733.705d78","type":"join","z":"30c08
38d.13792c","name":"","mode":"custom","build":"string","proper
ty":"payload","propertyType":"msg","key":"topic","joiner":"
","joinerType":"str","accumulate":false,"timeout":"","count":"
2","reduceRight":false,"reduceExp":"","reduceInit":"","reduceI
nitType":"","reduceFixup":"","x":803,"y":2840,"wires":[["2180c
447.226a4c"]]},{"id":"7acc1117.c59ce","type":"join","z":"30c08
38d.13792c","name":"","mode":"custom","build":"string","proper
ty":"payload","propertyType":"msg","key":"topic","joiner":"
","joinerType":"str","accumulate":false,"timeout":"","count":"
2","reduceRight":false,"reduceExp":"","reduceInit":"","reduceI
nitType":"","reduceFixup":"","x":803,"y":2880,"wires":[["2180c
447.226a4c"]]},{"id":"1c2e1167.8af3af","type":"change","z":"30
c0838d.13792c","name":"","rules":[{"t":"set","p":"payload","pt
":"msg","to":"$string(msg.payload)\t","tot":"jsonata"}],"actio
n":"","property":"","from":"","to":"","reg":false,"x":812,"y":
2960,"wires":[["43b4144b.689a7c"]]},{"id":"43b4144b.689a7c","t
ype":"change","z":"30c0838d.13792c","name":"","rules":[{"t":"c
hange","p":"payload","pt":"msg","from":"T","fromt":"str","to":
"
","tot":"str"}],"action":"","property":"","from":"","to":"","r
eg":false,"x":1012,"y":2960,"wires":[["8a6ee3ac.5f23d"]]},{"id
":"8a6ee3ac.5f23d","type":"split","z":"30c0838d.13792c","name"
:"","splt":"20","spltType":"len","arraySplt":"1","arraySpltTyp
e":"len","stream":false,"addname":"","x":1182,"y":2960,"wires"
:[["7acc1117.c59ce"]]},{"id":"bd706ae9.988318","type":"change"
,"z":"30c0838d.13792c","name":"","rules":[{"t":"set","p":"payl
oad","pt":"msg","to":"$string(msg.payload)\t","tot":"jsonata"}
],"action":"","property":"","from":"","to":"","reg":false,"x":
812,"y":2920,"wires":[["f3125788.267878"]]},{"id":"f3125788.26
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[{"t":"change","p":"payload","pt":"msg","from":"T","fromt":"st
r","to":"
","tot":"str"}],"action":"","property":"","from":"","to":"","r
eg":false,"x":1012,"y":2920,"wires":[["c6a37711.bc3778"]]},{"i
d":"c6a37711.bc3778","type":"split","z":"30c0838d.13792c","nam

e":"","splt":"20","spltType":"len","arraySplt":"1","arraySpltT
ype":"len","stream":false,"addname":"","x":1182,"y":2920,"wire
s":[["d5b1c733.705d78"]]},{"id":"62f320af.21429","type":"debug
","z":"30c0838d.13792c","name":"","active":true,"tosidebar":tr
ue,"console":false,"tostatus":false,"complete":"false","x":168
2,"y":2982,"wires":[]},{"id":"4feef5d8.2df1bc","type":"cos-
qry","z":"30c0838d.13792c","name":"","list":"1","bucket":"hive
-dtp1-current-
state","maxkeys":50,"cosconfig":"57e1b701.1c2418","x":372,"y":
2860,"wires":[["73c94ff8.834b4","20a8d3d2.987d7c","68cf7c49.d2
33a4","24dd9ada.4f4536"]]},{"id":"50157389.b285ec","type":"inj
ect","z":"30c0838d.13792c","name":"","topic":"","payload":"","
payloadType":"date","repeat":"","crontab":"","once":false,"onc
eDelay":0.1,"x":112,"y":3045,"wires":[["ed5ac102.c401b"]]},{"i
d":"6a59c3b8.d8099c","type":"join","z":"30c0838d.13792c","name
":"","mode":"custom","build":"string","property":"payload","pr
opertyType":"msg","key":"topic","joiner":"\\n","joinerType":"s
tr","accumulate":false,"timeout":"","count":"2","reduceRight":
false,"reduceExp":"","reduceInit":"","reduceInitType":"","redu
ceFixup":"","x":1024,"y":3045,"wires":[["3425aa1d.9de876"]]},{
"id":"3425aa1d.9de876","type":"ui_template","z":"30c0838d.1379
2c","group":"f909c0f6.09a4d","name":"","order":6,"width":0,"he
ight":0,"format":"<style>\n   #mylog {\n   min-height:
95px;\n   min-width: 145px;\n   padding: 0;\n
background-color: #F0F8FF;\n   white-space: pre;\n
font-size: 15px;\n   text-align: right;\n
}\n</style>\n\n<div id=\"mylog\" ng-bind=\"msg.payload\"
contenteditable=\"true\">\n   <!-- payload will go here --
>\n \n\n\n","storeOutMessages":true,"fwdInMessages":true,
"resendOnRefresh":true,"templateScope":"local","x":1512,"y":31
65,"wires":[["52a6b0cf.2f79e"]]},{"id":"1332209b.8999ef","type
":"function","z":"30c0838d.13792c","name":"EmptyList","func":"
msg.payload = \"\";\nreturn
msg;","outputs":1,"noerr":0,"x":302,"y":3165,"wires":[["3425aa
1d.9de876"]]},{"id":"dfabe56.cc53f18","type":"function","z":"3
0c0838d.13792c","name":"FileName","func":"msg.payload =
msg.payload[0].Key;\n\n\n\nreturn
msg;\n\n","outputs":1,"noerr":0,"x":634,"y":3025,"wires":[["9b
45867f.8a9c78"]]},{"id":"896b6d2f.be8d9","type":"function","z"
:"30c0838d.13792c","name":"FileName","func":"msg.payload =
msg.payload[1].Key;\n\nreturn
msg;\n\n","outputs":1,"noerr":0,"x":634,"y":3065,"wires":[["d1
8169b8.e7dd38"]]},{"id":"324f636e.8b958c","type":"function","z
":"30c0838d.13792c","name":"DateTime","func":"msg.payload =
msg.payload[0].LastModified;\nreturn
msg;","outputs":1,"noerr":0,"x":632,"y":3105,"wires":[["c6d3bb
83.879428"]]},{"id":"9698465b.e192b8","type":"function","z":"3
0c0838d.13792c","name":"DateTime","func":"msg.payload =
msg.payload[1].LastModified;\nreturn

msg;","outputs":1,"noerr":0,"x":632,"y":3145,"wires":[["8323dd
94.4b0a2"]]},{"id":"9b45867f.8a9c78","type":"join","z":"30c083
8d.13792c","name":"","mode":"custom","build":"string","propert
y":"payload","propertyType":"msg","key":"topic","joiner":"
","joinerType":"str","accumulate":false,"timeout":"","count":"
2","reduceRight":false,"reduceExp":"","reduceInit":"","reduceI
nitType":"","reduceFixup":"","x":804,"y":3025,"wires":[["6a59c
3b8.d8099c"]]},{"id":"d18169b8.e7dd38","type":"join","z":"30c0
838d.13792c","name":"","mode":"custom","build":"string","prope
rty":"payload","propertyType":"msg","key":"topic","joiner":"
","joinerType":"str","accumulate":false,"timeout":"","count":"
2","reduceRight":false,"reduceExp":"","reduceInit":"","reduceI
nitType":"","reduceFixup":"","x":804,"y":3065,"wires":[["6a59c
3b8.d8099c"]]},{"id":"8323dd94.4b0a2","type":"change","z":"30c
0838d.13792c","name":"","rules":[{"t":"set","p":"payload","pt"
:"msg","to":"$string(msg.payload)\t","tot":"jsonata"}],"action
":"","property":"","from":"","to":"","reg":false,"x":812,"y":3
145,"wires":[["49a0a81.f5b8358"]]},{"id":"49a0a81.f5b8358","ty
pe":"change","z":"30c0838d.13792c","name":"","rules":[{"t":"ch
ange","p":"payload","pt":"msg","from":"T","fromt":"str","to":"
","tot":"str"}],"action":"","property":"","from":"","to":"","r
eg":false,"x":1012,"y":3145,"wires":[["3ee814d.29403ec"]]},{"i
d":"3ee814d.29403ec","type":"split","z":"30c0838d.13792c","nam
e":"","splt":"20","spltType":"len","arraySplt":"1","arraySpltT
ype":"len","stream":false,"addname":"","x":1182,"y":3145,"wire
s":[["d18169b8.e7dd38"]]},{"id":"c6d3bb83.879428","type":"chan
ge","z":"30c0838d.13792c","name":"","rules":[{"t":"set","p":"p
ayload","pt":"msg","to":"$string(msg.payload)\t","tot":"jsonat
a"}],"action":"","property":"","from":"","to":"","reg":false,"
x":812,"y":3105,"wires":[["b43539d.f0d49c8"]]},{"id":"b43539d.
f0d49c8","type":"change","z":"30c0838d.13792c","name":"","rule
s":[{"t":"change","p":"payload","pt":"msg","from":"T","fromt":
"str","to":"
","tot":"str"}],"action":"","property":"","from":"","to":"","r
eg":false,"x":1012,"y":3105,"wires":[["3ea4e9e7.2a2976"]]},{"i
d":"3ea4e9e7.2a2976","type":"split","z":"30c0838d.13792c","nam
e":"","splt":"20","spltType":"len","arraySplt":"1","arraySpltT
ype":"len","stream":false,"addname":"","x":1182,"y":3105,"wire
s":[["9b45867f.8a9c78"]]},{"id":"52a6b0cf.2f79e","type":"debug
","z":"30c0838d.13792c","name":"","active":true,"tosidebar":tr
ue,"console":false,"tostatus":false,"complete":"false","x":168
2,"y":3165,"wires":[]},{"id":"ed5ac102.c401b","type":"cos-
qry","z":"30c0838d.13792c","name":"","list":"1","bucket":"hive
-dtp1-future-
state","maxkeys":50,"cosconfig":"c4d654bf.aa43a8","x":372,"y":
3045,"wires":[["dfabe56.cc53f18","896b6d2f.be8d9","324f636e.8b
958c","9698465b.e192b8"]]},{"id":"73589a4a.f7c484","type":"cos
-
qry","z":"30c0838d.13792c","name":"","list":"1","bucket":"hive

-dtp1-as-
designed","maxkeys":50,"cosconfig":"c7ac24ca.6ff278","x":370,"
y":2560,"wires":[["3dfc9d1a.ac33c2","d4bf2ac9.0e0a58","cb08259
8.c7f5a8","3daa8b63.c56964"]]},{"id":"f909c0f6.09a4d","type":"
ui_group","z":"","name":"Cloud
Interface","tab":"aa362ab0.4c6808","disp":true,"width":"6","co
llapse":false},{"id":"2d70ae41.1ad462","type":"cos-
config","z":"","apiKeyId":"---API_KEY---","location":"eu-
gb","ibmAuthEndpoint":"https://iam.cloud.ibm.com/oidc/token","
endpoint":"s3.eu-gb.cloud-object-
storage.appdomain.cloud","serviceInstanceId":"Cloud Object
Storage-
1v","hmac":false,"accesskeyid":"","accesskey":"","name":"hive-
dtp-as-manufactured"},{"id":"57e1b701.1c2418","type":"cos-
config","z":"","apiKeyId":"---API_KEY---","location":"eu-
gb","ibmAuthEndpoint":"https://iam.cloud.ibm.com/oidc/token","
endpoint":"s3.eu-gb.cloud-object-
storage.appdomain.cloud","serviceInstanceId":"Cloud Object
Storage-
1v","hmac":false,"accesskeyid":"","accesskey":"","name":"hive-
dtp1-current-state"},{"id":"c4d654bf.aa43a8","type":"cos-
config","z":"","apiKeyId":"---API_KEY---","location":"eu-
gb","ibmAuthEndpoint":"https://iam.cloud.ibm.com/oidc/token","
endpoint":"s3.eu-gb.cloud-object-
storage.appdomain.cloud","serviceInstanceId":"Cloud Object
Storage-
1v","hmac":false,"accesskeyid":"","accesskey":"","name":"hive-
dtp1-future-state"},{"id":"c7ac24ca.6ff278","type":"cos-
config","z":"","apiKeyId":"---API_KEY---","location":"eu-
gb","ibmAuthEndpoint":"https://iam.cloud.ibm.com/oidc/token","
endpoint":"s3.eu-gb.cloud-object-
storage.appdomain.cloud","serviceInstanceId":"Cloud Object
Storage-
1v","hmac":false,"accesskeyid":"","accesskey":"","name":"hive-
dtp1-as-
designed"},{"id":"aa362ab0.4c6808","type":"ui_tab","z":"","nam
e":"EoL Fwd
Planning","icon":"dashboard","disabled":false,"hidden":false}]

APPENDIX B – NODERED CODE (SERVER SIDE)

Contained in this appendix is the Node-RED code running on the server (flow is shown in Figure 7-3).

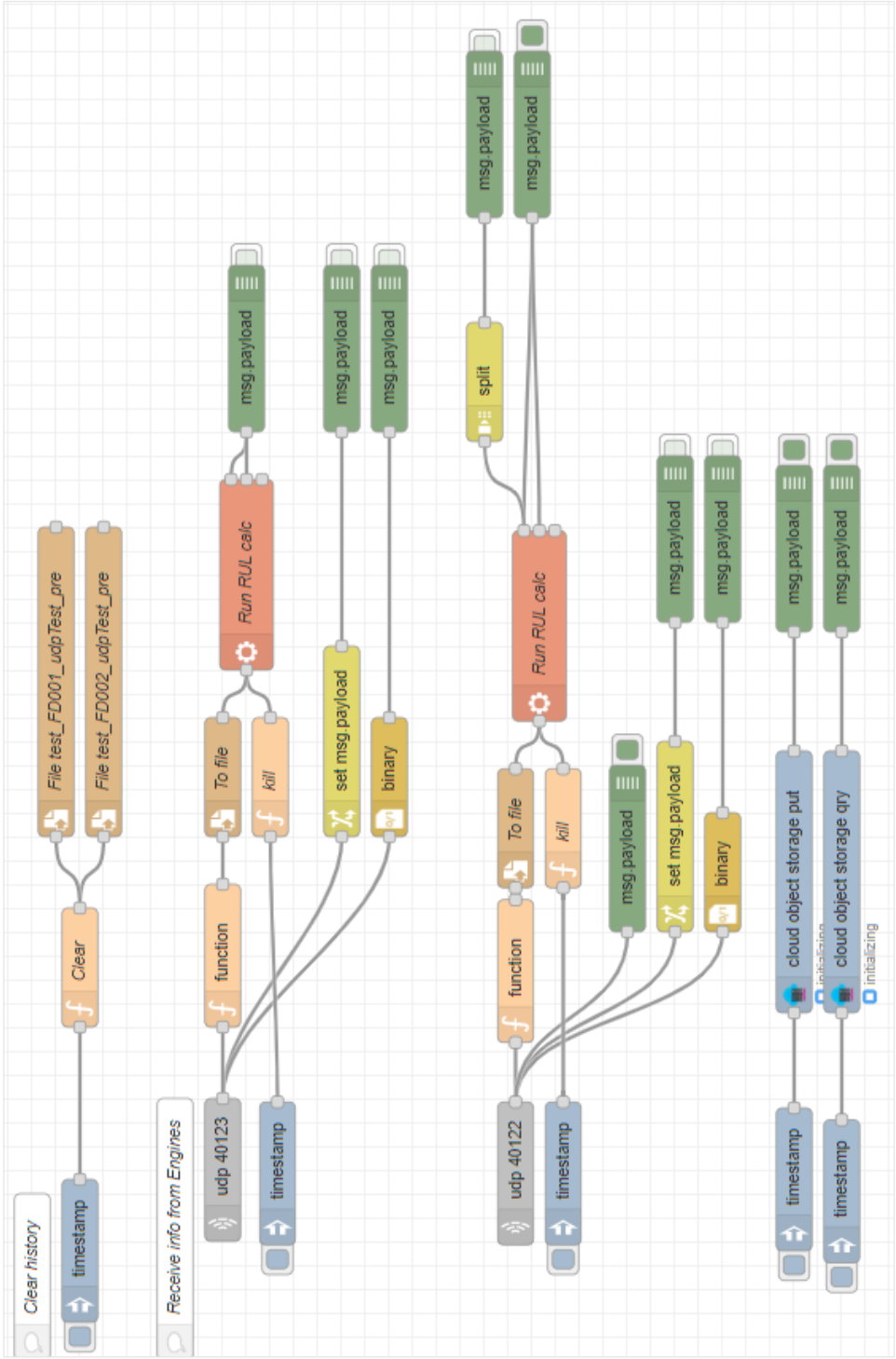

Figure 7-3 - The Node-RED flow for Appendix B code

‘Clear History’ Code

This flow is used to clear data before initialising the system that mimic the engine and digital twin prototype. . File addresses, personal email addresses, API, subscribe, and publish keys will be removed and replaced with “---_FILE_PATH---”, “---E-MAIL---”, “---API_KEY---”, “---Sub_KEY---” and “---Pub_KEY---” respectively, for security reasons.


```
[{"id":"3903df73.ec2ae","type":"file","z":"b03f1a69.d0d798","n
ame":"File test_FD001_udpTest_pre","filename":"C:\\Users---
FILE_PATH---
\\test_FD001_udpTest_pre.txt","appendNewline":false,"createDir
":false,"overwriteFile":"true","encoding":"none","x":570,"y":8
0,"wires":[[]]},{"id":"a24ab070.6a2bd","type":"function","z":"
b03f1a69.d0d798","name":"Clear","func":"msg.payload =
\"\";\nreturn
msg;","outputs":1,"noerr":0,"x":330,"y":100,"wires":[["2ffebb6
a.3f3504","3903df73.ec2ae"]]},{"id":"2ffebb6a.3f3504","type":"
file","z":"b03f1a69.d0d798","name":"File
test_FD002_udpTest_pre","filename":"C:\\Users\\---FILE_PATH---
\\test_FD002_udpTest_pre.txt","appendNewline":false,"createDir
":false,"overwriteFile":"true","encoding":"none","x":570,"y":1
20,"wires":[[]]},{"id":"99baca28.8354f8","type":"comment","z":
"b03f1a69.d0d798","name":"Clear
history","info":"","x":70,"y":60,"wires":[]},{"id":"b290bb7e.a
c8718","type":"inject","z":"b03f1a69.d0d798","name":"","repeat
":"","crontab":"","once":false,"onceDelay":0.1,"topic":"","pay
load":"","payloadType":"date","x":92,"y":100,"wires":[["a24ab0
70.6a2bd"]]}]
```

‘Receive info from Engines’ Code

These flows listen for UDP messages transmitted by the engine simulator. Once the data has been received it is stored in a file, with each newly arrived set of readings being added to the file to build the historic dataset. Once stored, the flow triggers the running of the RUL calculations MATLAB file RULTest_ForDT_EngineX (Appendix C) that uses all data in the file to improve the estimation.


```
[{"id":"473d99e5.ca3f68","type":"exec","z":"b03f1a69.d0d798","
command":"matlab -batch
\"RULTest_ForDT_Engine1\"","addpay":false,"append":"","useSpaw
n":"false","timer":"","oldrc":false,"name":"Run RUL
calc","x":660,"y":240,"wires":[["d4664afc.3ea118"],["d4664afc.
3ea118"],[]]},{"id":"d4664afc.3ea118","type":"debug","z":"b03f
1a69.d0d798","name":"","active":false,"tosidebar":true,"consol
e":false,"tostatus":false,"complete":"false","x":850,"y":240,"
wires":[]},{"id":"df340e98.fff42","type":"udp
in","z":"b03f1a69.d0d798","name":"","iface":"","port":"40123",
"ipv":"udp4","multicast":"false","group":"","datatype":"buffer
","x":160,"y":220,"wires":[["ef65a56b.dc67a8","b306494.baf5db8
","c870cede.23a45"]]},{"id":"8c19a90f.0bb838","type":"function
","z":"b03f1a69.d0d798","name":"kill","func":"delete
msg.payload;\nmsg.kill=\"SIGKILL\";\nreturn
msg;","outputs":1,"noerr":0,"x":490,"y":260,"wires":[["473d99e
5.ca3f68"]]},{"id":"d5ef8f0d.ae12c","type":"inject","z":"b03f1
a69.d0d798","name":"","repeat":"","crontab":"","once":false,"o
nceDelay":0.1,"topic":"","payload":"","payloadType":"date","x"
:157,"y":266,"wires":[["8c19a90f.0bb838"]]},{"id":"8f6fe1ad.a4
66e","type":"debug","z":"b03f1a69.d0d798","name":"","active":f
alse,"tosidebar":true,"console":false,"tostatus":false,"comple
te":"false","x":850,"y":320,"wires":[]},{"id":"ef65a56b.dc67a8
","type":"change","z":"b03f1a69.d0d798","name":"","rules":[{"t
":"set","p":"payload","pt":"msg","to":"","tot":"str"}],"action
":"","property":"","from":"","to":"","reg":false,"x":520,"y":3
20,"wires":[["8f6fe1ad.a466e"]]},{"id":"adb6f39b.cb57d","type"
:"debug","z":"b03f1a69.d0d798","name":"","active":false,"tosid
ebar":true,"console":false,"tostatus":false,"complete":"false"
,"x":850,"y":360,"wires":[]},{"id":"b306494.baf5db8","type":"b
inary","z":"b03f1a69.d0d798","name":"","property":"payload","p
attern":"x32,l32f","x":490,"y":360,"wires":[["adb6f39b.cb57d"]
]},{"id":"c870cede.23a45","type":"function","z":"b03f1a69.d0d7
98","name":"","func":"msg.payload =
msg.payload.toString();\nreturn
msg;","outputs":1,"noerr":0,"x":340,"y":220,"wires":[["9065fca
```

6.ba08f"]]},{"id":"9065fca6.ba08f","type":"file","z":"b03f1a69
.d0d798","name":"To file","filename":"C:\\Users\\---FILE_PATH-
--
\\test_FD001_udpTest_pre.txt","appendNewline":true,"createDir"
:false,"overwriteFile":"false","encoding":"none","x":490,"y":2
20,"wires":[["473d99e5.ca3f68"]]},{"id":"e99e0963.2c9058","typ
e":"exec","z":"b03f1a69.d0d798","command":"matlab -batch
\"RULTest_ForDT_Engine2\"","addpay":false,"append":"","useSpaw
n":"false","timer":"","oldrc":false,"name":"Run RUL
calc","x":617,"y":486,"wires":[["1352a8d6.3f70f7","d1a7c9ee.93
9398"],["1352a8d6.3f70f7"],[]]},{"id":"1352a8d6.3f70f7","type"
:"debug","z":"b03f1a69.d0d798","name":"","active":true,"toside
bar":true,"console":false,"tostatus":false,"complete":"false",
"x":1030,"y":480,"wires":[]},{"id":"f2f68a10.81b6f8","type":"u
dp
in","z":"b03f1a69.d0d798","name":"","iface":"","port":"40122",
"ipv":"udp4","multicast":"false","group":"","datatype":"buffer
","x":157,"y":466,"wires":[["c11dce65.2acdc","37a158df.d97e98"
,"23de111b.7279ce","18d1dcf1.aa3bb3"]]},{"id":"aaa2fe96.62b67"
,"type":"function","z":"b03f1a69.d0d798","name":"kill","func":
"delete msg.payload;\nmsg.kill=\"SIGKILL\";\nreturn
msg;","outputs":1,"noerr":0,"x":447,"y":506,"wires":[["e99e096
3.2c9058"]]},{"id":"11719c93.3a1683","type":"inject","z":"b03f
1a69.d0d798","name":"","repeat":"","crontab":"","once":false,"
onceDelay":0.1,"topic":"","payload":"","payloadType":"date","x
":157,"y":506,"wires":[["aaa2fe96.62b67"]]},{"id":"e219deb3.b3
a8d","type":"debug","z":"b03f1a69.d0d798","name":"","active":f
alse,"tosidebar":true,"console":false,"tostatus":false,"comple
te":"false","x":690,"y":600,"wires":[]},{"id":"c11dce65.2acdc"
,"type":"change","z":"b03f1a69.d0d798","name":"","rules":[{"t"
:"set","p":"payload","pt":"msg","to":"","tot":"str"}],"action"
:"","property":"","from":"","to":"","reg":false,"x":440,"y":60
0,"wires":[["e219deb3.b3a8d"]]},{"id":"99343574.c733e8","type"
:"debug","z":"b03f1a69.d0d798","name":"","active":false,"tosid
ebar":true,"console":false,"tostatus":false,"complete":"false"
,"x":690,"y":640,"wires":[]},{"id":"37a158df.d97e98","type":"b
inary","z":"b03f1a69.d0d798","name":"","property":"payload","p
attern":"x32,l32f","x":410,"y":640,"wires":[["99343574.c733e8"
]]},{"id":"23de111b.7279ce","type":"function","z":"b03f1a69.d0
d798","name":"","func":"msg.payload =
msg.payload.toString();\nreturn
msg;","outputs":1,"noerr":0,"x":327,"y":466,"wires":[["a34f196
e.bd6618"]]},{"id":"a34f196e.bd6618","type":"file","z":"b03f1a
69.d0d798","name":"To file","filename":"C:\\Users\\---
FILE_PATH---
\\test_FD002_udpTest_pre.txt","appendNewline":true,"createDir"
:false,"overwriteFile":"false","encoding":"none","x":447,"y":4
66,"wires":[["e99e0963.2c9058"]]},{"id":"9405fc44.efa6","type"
:"comment","z":"b03f1a69.d0d798","name":"Receive info from

Engines","info":"","x":110,"y":180,"wires":[]},{"id":"d1a7c9ee
.939398","type":"split","z":"b03f1a69.d0d798","name":"","splt"
:"\\n","spltType":"str","arraySplt":1,"arraySpltType":"len","s
tream":false,"addname":"","x":822,"y":440,"wires":[["b117a3a4.
90a99"]]},{"id":"b117a3a4.90a99","type":"debug","z":"b03f1a69.
d0d798","name":"","active":false,"tosidebar":true,"console":fa
lse,"tostatus":false,"complete":"false","x":1030,"y":440,"wire
s":[]},{"id":"18d1dcf1.aa3bb3","type":"debug","z":"b03f1a69.d0
d798","name":"","active":true,"tosidebar":true,"console":false
,"tostatus":false,"complete":"false","x":430,"y":560,"wires":[
]},{"id":"83854153.58514","type":"cos-
put","z":"b03f1a69.d0d798","name":"","bucket":"hive-
dtp","create":"0","objectname":"Mock Trent
Step.stp","mode":"0","filepath":"C:\\Users\\---FILE_PATH---
\\Trent 900 Step","filename":"Mock Trent
Step.stp","contentType":"image/png","geturl":false,"cosconfig"
:"741a221.49392dc","x":402,"y":700,"wires":[["ad04eb77.47d868"
]]},{"id":"ad04eb77.47d868","type":"debug","z":"b03f1a69.d0d79
8","name":"","active":true,"tosidebar":true,"console":false,"t
ostatus":false,"complete":"false","statusVal":"","statusType":
"auto","x":682,"y":700,"wires":[]},{"id":"d8385149.71a5e","typ
e":"inject","z":"b03f1a69.d0d798","name":"","props":[{"p":"pay
load"},{"p":"topic","vt":"str"}],"repeat":"","crontab":"","onc
e":false,"onceDelay":0.1,"topic":"","payload":"","payloadType"
:"date","x":152,"y":700,"wires":[["83854153.58514"]]},{"id":"2
b218469.a7d69c","type":"inject","z":"b03f1a69.d0d798","name":"
","props":[{"p":"payload"},{"p":"topic","vt":"str"}],"repeat":
"","crontab":"","once":false,"onceDelay":0.1,"topic":"","paylo
ad":"","payloadType":"date","x":142,"y":740,"wires":[["15e8ae8
e.15aa11"]]},{"id":"15e8ae8e.15aa11","type":"cos-
qry","z":"b03f1a69.d0d798","name":"","list":"0","bucket":"hive
-
dtp1","maxkeys":50,"cosconfig":"741a221.49392dc","x":402,"y":7
40,"wires":[["1fe824c9.6287fb"]]},{"id":"1fe824c9.6287fb","typ
e":"debug","z":"b03f1a69.d0d798","name":"","active":true,"tosi
debar":true,"console":false,"tostatus":false,"complete":"false
","statusVal":"","statusType":"auto","x":682,"y":740,"wires":[
]},{"id":"741a221.49392dc","type":"cos-config","apiKeyId":"---
API_KEY---","location":"eu-
gb","ibmAuthEndpoint":"https://iam.cloud.ibm.com/oidc/token","
endpoint":"s3.eu-gb.cloud-object-
storage.appdomain.cloud","serviceInstanceId":"cloud-object-
storage","hmac":false,"accesskeyid":"","accesskey":"","name":"
hive-dtp1"}]

APPENDIX C – MATLAB CODE

Contained in this appendix is a list of the measured engine parameters (Table 7-1) taken from (Saxena and Goebel, 2008) and the MATLAB code for file RULTest_ForDT_Engine1.m.

Table 7-1 List of engine parameters used in this work

Altitude ft	epr Engine pressure ratio (P50/P2) --
Mach Number	Ps30 Static pressure at HPC outlet psia
Sea-level temperature °F	phi Ratio of fuel flow to Ps30 pps/psi
T2 Total temperature at fan inlet °R	NRf Corrected fan speed rpm
T24 Total temperature at LPC outlet °R	NRc Corrected core speed rpm
T30 Total temperature at HPC outlet °R	BPR Bypass Ratio --
T50 Total temperature at LPT outlet °R	farB Burner fuel-air ratio --
P2 Pressure at fan inlet psia	htBleed Bleed Enthalpy --
P15 Total pressure in bypass-duct psia	Nf_dmd Demanded fan speed rpm
P30 Total pressure at HPC outlet psia	PCNfR_dmd Demanded corrected fan speed rpm
Nf Physical fan speed rpm	W31 HPT coolant bleed lbm/s
Nc Physical core speed rpm	W32 LPT coolant bleed lbm/s

This script is a modified MathWorks (2020) sequence-to-sequence regression using deep learning example code. It imports a deep neural network that has already been trained using a long short-term memory (LSTM) network and the Saxena and Goebel (2008) test_FD001.txt dataset. The test_FD001.txt dataset contains run-to-failure data for 100 engines. The network and training parameters were as per the example in MathWorks (2020) apart from maxEpochs that were increased to 100 from 60. The behaviour of the training progress chart had suggested the network was not fully trained at 60 epochs. Training the network 50 times at both 60 and 100 epochs and logging the RMSE demonstrated the improvement in repeatability due to this

single parameter change (Figure 7-4). Standard deviation reduced from 2.6 to 1.7. Other modifications were found not to benefit so no further optimisation of the parameters was performed.

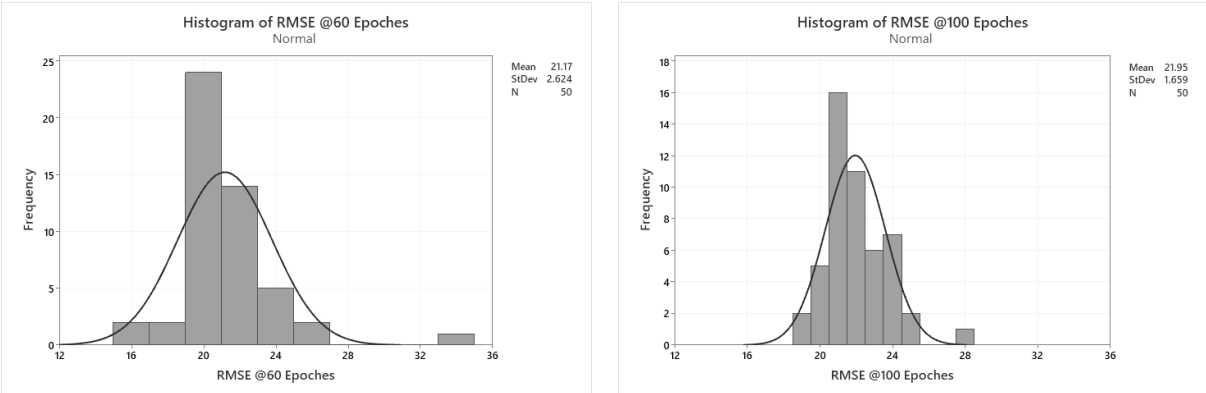

Figure 7-4 - The effect of modifying training parmeters on standard deviation of RMSE

Lau, S. (2017). "Prognostics Center of Excellence." Retrieved 01/07/2020, from https://ti.arc.nasa.gov/tech/dash/groups/pcoe/.

MathWorks. (2020). "Sequence-to-Sequence Regression Using Deep Learning." Retrieved 05/06/2020, from https://uk.mathworks.com/help/deeplearning/ug/sequence-to-sequence-regression-using-deep-learning.html.

Saxena, A. and K. Goebel (2008). Turbofan Engine Degradation Simulation Data Set. NASA Ames Prognostics Data Repository. NASA Ames Research Center, Moffett Field, CA.

File Name: RULTest_ForDT_Engine1.m

```
%This file contains modified MATLAB Example code -
"SequencetoSequenceRegressionUsingDeepLEarningExample.mlx"

clc
clear

load savedNet.mat
filenamePredictors = fullfile("test_FD001_udpTest_pre.txt");
filenameResponses = fullfile("RUL_FD001UDP.txt");
[XTest,YTest] =
prepareDataTestUDP(filenamePredictors,filenameResponses);

for i = 1:numel(XTest)
    XTest{i}(idxConstant,:) = [];
    XTest{i} = (XTest{i} - mu) ./ sig;
    YTest{i}(YTest{i} > thr) = thr;
end

%The below line calls and runs the function
predictionTestUDP

%Plot RMSE
figure
rmse = sqrt(mean((YPredLast - YTestLast).^2));
histogram(YPredLast - YTestLast)

 R = round(YPred{1}(end));
    ExpiryDate = double(tNew + R);
    NewExpiryDate = datestr(ExpiryDate,0);

title("RMSE = " + rmse + "  RUL for engine1 = " +
YPred{1}(end))
ylabel("Frequency")
xlabel("Error")

YPredLast1Transpose = transpose(YPredLast);
writematrix(YPredLast1Transpose, 'YPredLast1.txt')

YPredLast1Transpose = readmatrix('YPredLast1.txt')
AllYPredLasts = [YPredLast1Transpose]
% System inputs
Threshold = 140;  % Threshold
RUL = YPredLast1Transpose % Estimated Remaining Useful Life
(mu)
Sigma = 1; % Standard deviation (sigma)
Samples = 100; % Number of random samples
```

```
x1 = normrnd(RUL,Sigma,[Samples,1]); % Generate the random
variables w.r.t to the normal distribution
pd = fitdist(x1,'Normal'); % fit distribution curve

% Display random variables
figure(1)
plot(x1)

% Display normal distribution generated from random variables
figure(2)
% x_axis_min = RUL-(RUL);
% x_axis_max = RUL+(RUL);
 x_axis_min = 0;
 x_axis_max = RUL*2;

x_axis = x_axis_min:(1/Samples):x_axis_max; % x-axis
y = pdf(pd,x_axis); % Probability Density Function
plot(x_axis,y,'LineWidth',2);
balanceIndices = find(x_axis==Threshold); % Find the x_axis
position when it equals Threshold

hold on

% Display on same figure the calculated eRUL as a dashed line
y2 = xline(RUL,'--','eRUL');

if Threshold <=x_axis_min
    A=0;

end

if Threshold >=x_axis_max
    A=100;

end

if Threshold >x_axis_min && Threshold <x_axis_max
    %Ythreshold=x_axis(ActualThreshold);
    y1=get(gca,'ylim');
    plot([Threshold Threshold] ,y1,'LineWidth',2);
    iz=linspace(x_axis(1),Threshold, Samples);
    yz=pdf(pd,iz);
    area(iz,yz);
    txt = '\leftarrow threshold';
    text(Threshold,((Sigma)/5),txt)

 hold off
```

```
    arrX_values = x_axis(1:balanceIndices);
    arrY_values = y(1:balanceIndices);
    A = trapz(arrX_values(), arrY_values()); % Take x_axis

else
    y1=get(gca,'ylim');
    plot([Threshold Threshold] ,y1,'LineWidth',2);
    iz=linspace(x_axis(1),Threshold, Samples);
    yz=pdf(pd,iz);
    area(iz,yz);
    txt1 = '\leftarrow threshold';
   text(Threshold,((Sigma)/5),txt1)

  hold off

end

A_percent = A*100;
failure_probability = [num2str(A_percent),'%'];
disp(failure_probability)

if A_percent > 50
  message = (' Consider_Reman ');
    disp(message)

else
  message = (' In_Use ');
    disp(message)
end

failure_probability_message = [A_percent,message]
writematrix(failure_probability_message,
'failure_probability.txt', 'WriteMode','append')

Failure_string = [num2str(AllYPredLasts),'
',num2str(A_percent), message]

writematrix(Failure_string, 'AllYPredLasts.txt')
putFile(raspi,'AllYPredLasts.txt','/home/pi/gps/Adafruit_circu
itPython_Bundle/Adafruit_circuitPython_GPS/examples')


-----------------------------------------------------------------
------
File Name: predictionTestUDP.m

%idx = randperm(numel(1),1); %20:25;
figure
```

```
t = datetime('now','TimeZone','local','Format','d-MMM-y');
tNew = datenum(t);

for i = 1:numel(idx)
   % fprintf(testfile,'%6.2f %12.8f\r\n',idx);
    subplot(1,1,i)

    plot(YTest{idx(i)},'--')
    hold on
    plot(YPred{idx(i)},'.-')
    hold off

    ylim([0 thr + 22])

    R = round(YPred{idx(i)}(end));
    ExpiryDate = double(tNew + R);
    NewExpiryDate = datestr(ExpiryDate,1); %1 represents the
type pf output, in this case its only day, month, year (e.g. )
incl time too)

    title("Test Observation " + idx(i)) %" ExpiryDate " +
NewExpiryDate)
    xlabel("Time Step")
    ylabel("RUL")
end
legend(["Test Data" "Predicted"],'Location','southeast')

for i = 1:numel(YTest)
    YTestLast(i) = YTest{i}(end);
    YPredLast(i) = YPred{i}(end);
end
```

APPENDIX D – PYTHON3 CODE

This code captures the signals from the GPS and sensors. Once the GPS is connected the readings from the other sensors are taken and the collective data is published using PubNub.

File Name: gps simpletest3.py

```
# Link code to GPS module and sensor demonstration.
# Wait for a fix then print a message with the current
location and sensor readings

import sys
import time
import board
import busio
import RPi.GPIO as GPIO # Import Raspberry Pi GPIO library
from time import sleep # Import the sleep function from the
time module

import adafruit_gps
import Adafruit_DHT

from Adafruit_BMP085Python3 import BMP085

import pubnub
from pubnub.pnconfiguration import PNConfiguration
from pubnub.pubnub import PubNub
from pubnub.callbacks import SubscribeCallback
from pubnub.enums import PNOperationType, PNStatusCategory

pnconfig = PNConfiguration()
pnconfig.subscribe_key = "sub-c-4d6dde7c-6fb6-11ea-a7c4-
5e95b827fd71"
pnconfig.publish_key = "pub-c-2ec6bdf6-2ff8-4b9b-89cf-
a2089c83254b"
pnconfig.ssl = False
pubnub = PubNub(pnconfig)

GPIO.setwarnings(False) # Ignore warning for now
GPIO.setmode(GPIO.BCM) # Use physical pin numbering
GPIO.setup(4, GPIO.OUT, initial=GPIO.HIGH) # Set pin 7 to be
an output pin and set initial value to low (off)

# DHT (humidity and temperature) physical set-up settings,
using DS1302 ("22) and connected to rpi GPIO25
```

```
sensor = 22
pin = 25

# BMP085 (barometric pressure) set-up
bmp = BMP085(0x77)

def publish_callback(results, status):
    pass
    # Handle PNPublishResult and PNStatus

# Create a serial connection for the GPS connection using the
pyserial library for uart access
import serial
uart = serial.Serial("/dev/ttyAMA0", baudrate=9600,
timeout=10)

# Create a GPS module instance
gps = adafruit_gps.GPS(uart, debug=False)  # Use UART/pyserial

# Initialize the GPS module by changing what data it sends and
at what rate
# Turn on the basic GGA and RMC info
gps.send_command(b"PMTK314,0,1,0,1,0,0,0,0,0,0,0,0,0,0,0,0,0,0
,0")

# Set update rate
gps.send_command(b"PMTK220,1000")

# Main loop runs continuously and prints the GPS module
location
last_print = time.monotonic()
while True:
    # Call gps.update() every loop iteration
    # Returns a bool that is true if it parsed new data
    gps.update()
    # Print out current location details if there is a fix
    current = time.monotonic()
    if current - last_print >= 20.0:
        last_print = current

        # Try to grab a sensor reading and use the read_retry
method
        # to 15 times to get a sensor reading
        humidity, temperature =
Adafruit_DHT.read_retry(sensor, pin)

        # Read the current temperature from BMP085
        temp = bmp.readTemperature()
```

```
        # Read the current barometric pressure level from
BMP085
        pressure = bmp.readPressure()

        # Calculate altitude based on an estimated mean sea
level pressure from BMP085
        altitude = bmp.readAltitude()

        # Sometimes there wont be a reading and the results
will be null (because Linux can't
        # guarantee the timing of calls to read the sensor).
If this happens try again!
        if humidity is not None and temperature is not None:
            print("=" * 40)  # Print a separator line.
            print("ENVIRONMENTAL CONDITIONS")
            print(("-") * 40)  # Print a separator line.
            print('Ambient Temperature:{0:0.1f}*C
Humidity:{1:0.1f}%'.format(temperature, humidity))

        else:
            print('Failed to get reading. Try again!')
            sys.exit(1)

        if not gps.has_fix:
            # Try again if there is no fix yet.
            print("Waiting for fix...")
            continue
        # There is a fix - gps.has_fix = TRUE
        # Print out details about the fix like location, date,
etc.
        print("=" * 40)  # Print a separator line.
        print("CURRENT LOCATION AND GPS INFO")
        print(("-") * 40)  # Print a separator line.
        print(
            "Fix UTC timestamp: {}/{}/{}
{:02}:{:02}:{:02}".format(
                gps.timestamp_utc.tm_mon,  # Grab parts of the
time from the struct_time object that holds the fix time.
                gps.timestamp_utc.tm_mday,
                gps.timestamp_utc.tm_year,
                gps.timestamp_utc.tm_hour,
                gps.timestamp_utc.tm_min,
                gps.timestamp_utc.tm_sec,
            )
        )
        print("Temperature from BMP: %.2f C" % temp)
        print("Pressure from BMP:    %.2f hPa" % (pressure /
100.0))
        print("Altitude from BMP:    %.2f" % altitude)
```

```
        print("Latitude: {0:.6f}
degrees".format(gps.latitude))
        print("Longitude: {0:.6f}
degrees".format(gps.longitude))
        print("Fix quality: {}".format(gps.fix_quality))
        dictionary = {"temp": temp, "pressure": pressure,
"latitude": gps.latitude, "longitude": gps.longitude,
"altitude": gps.altitude_m, "month": gps.timestamp_utc.tm_mon,
"day": gps.timestamp_utc.tm_mday, "year":
gps.timestamp_utc.tm_year, "hour": gps.timestamp_utc.tm_hour,
"minute": gps.timestamp_utc.tm_min, "seconds":
gps.timestamp_utc.tm_sec, "temperature": temperature,
"humidity": humidity}

pubnub.publish().channel('channel').message(dictionary).pn_asy
nc(publish_callback)
        #while True: Run forever

        # and might not be present.  Check if they are None
before trying to use.
        if gps.satellites is not None:
            print("# satellites: {}".format(gps.satellites))
        if gps.altitude_m is not None:
            print("Altitude: {}
meters".format(gps.altitude_m))
        if gps.speed_knots is not None:
            print("Speed: {} knots".format(gps.speed_knots))
        if gps.track_angle_deg is not None:
            print("Track angle: {}
degrees".format(gps.track_angle_deg))
        if gps.horizontal_dilution is not None:
            print("Horizontal dilution:
{}".format(gps.horizontal_dilution))
        if gps.height_geoid is not None:
            print("Height geo ID: {}
meters".format(gps.height_geoid))
        print("=" *40)

print("Hello " + sys.argv[1])
```

APPENDIX E – DECISION MAKING MODULE DATA

This appendix documents the raw data used for the case study in section 6.2.4.

Table 7-2 Remanufacturing facility process information for DMM validation (1/5)

General Info			**Material value**	GBP/kg	USD/kg
All cost are presented in GBP	£		Aluminium	1.5375	2.05
Exchange (USD to GBP)	0.75		Cast Iron	0.15	0.2
Approx. new engine purchasing price	38000		Steel / Alloy steel	0.357	0.476
Profit margin target	8%		Polymer	0.05	
Remanufactured sales price vs new sales price	0.7		Stainless Steel	0.5	
Direct sale price of used vs new sales price	0.25		Cost to sperate / sort for recycling as a %age of disassembly time	2%	
SP - Remanufactured sales target price	26600		Waste per kg estimate (considering landfill tax + disposal management)	£0.20	
Remanufactured cost target threshold	TBC				
Labour rate per hour (incl. social sec., holidays, pension contrib. etc.)	18		**Processing Preference**		
Labour vs. Equip. OH ratio	1:6.25		1	Reuse	
CHEP pallet size (1200x1000x1600)	1.92		2	Reman.	
Pallet store per hour (based on ~£3 per week)	0.018		3	Recycle	
Hourly storage cost / m^3 (£)	0.009		4	Dispose	
Engine assembly time in hrs (based on 1 operator)	24				
CPF - Cost of finish (assumes all products are processed the same)	5000		**Inputs**		
th - in hours (assumes products identified for reuse are stored for 90 days)	2160		qj = qi	0.543	
m - missing parts (assumed to be zero)	0		TQ1 = 2-qi	1.457	
TS - second life time function	1.1		TQ2 = 3-2qj	1.914	
			TQ3= 2-qi	1.457	

Table 7-3 Remanufacturing facility process information for engine case study (2/5)

	General					EoL options				Life		USP
						sl		nsl				
Sub-assemblies	Estimated weights per component (kg)	Quantity (units)	Total weight of components (kg)	Primary material	Primary removal direction	fu - Components can flow into direct reuse Reuse (U)	fr - Components can flow into reman Reman. (R)	Recycle (C)	Dispose (D)	Total Options	Highest EoL opportunity	EoL *speciality
Cylinder block	600	1	600	Cast iron	-	0	1	1	1	3	R	*
Cylinder head assembly	38	6	228	Cast iron	+Z	0	1	1	1	3	R	*
Rocker assembly and injector	4	6	24	Mixed	+Z	0	0	1	1	2	C	
Rocker box	2	6	12	Aluminium	+Z	1	1	1	1	4	U	
Rocker covers	1	6	6	Polymer	+Z	1	0	1	1	3	U	
Valve train	20	6	120	Alloy	+Z	0	0	1	1	2	C	
Connecting rod	15	6	90	Steel	+Z	0	1	1	1	3	R	
Piston	6	6	36	Steel	+Z	0	1	1	1	3	R	
Sump	30	1	30	Aluminium	-Z	1	1	1	1	4	U	
Crankshaft	150	1	150	Steel	-Z	0	1	1	1	3	R	*
Main bearings	6	7	42	Cast iron	-Z	0	1	1	1	3	R	
Camshaft	50	1	50	Steel	-Y	0	1	1	1	3	R	*
Flywheel	80	1	80	Steel	+Y	0	1	1	1	3	R	
Damper	50	1	50	Steel	-Y	0	1	1	1	3	R	
Air cleaner	15	2	30	Polymer	+Z	1	1	1	1	4	U	
Exhaust pots	20	2	40	Steel	-X	1	1	1	1	4	U	
Starter motor	6	1	6	Mixed	-Y	1	0	1	1	3	U*	
Gears	50	1	50	Steel	-Y	0	1	1	1	3	R	
Gear cover	30	1	30	Aluminium	-Y	1	1	1	1	4	U	
Exhaust manifolds	10	1	10	Steel	-X	1	1	1	1	4	U	
Intake manifolds	10	1	10	Aluminium	+X	1	1	1	1	4	U	
Turbos	6	2	12	Alloy	-X	0	1	1	1	3	R	
Water pump	7	1	7	Cast iron	+X	0	1	1	1	3	R	
Alternator	6	1	6	Mixed	+Y	1	0	1	1	3	U*	
Lifting Brackets	3	2	6	Steel	+Z	1	1	1	1	4	U	
Flywheel housing	70	1	70	Cast iron	+Y	1	1	1	1	4	U	
Oil filter housing	2	3	6	Aluminium	+X	0	0	0	1	1	D	
Oil filter header	4	1	4	Aluminium	+X	1	1	1	1	4	U	
Cooler	20	1	20	Aluminium	+X	1	1	1	1	4	U	
Water pipes (multiple)	5	1	5	Aluminium	+X	1	1	1	1	4	U	
Rear plate	15	1	15	Steel	-Y	1	1	1	1	4	U	
Feet	2	2	4	Cast iron	-Y	1	1	1	1	4	U	
Oil pipes (multiple)	5	1	5	Aluminium	+X	0	0	1	1	2	C	
Fuel pipes (multiple)	4	1	4	Stainless steel	+X	0	0	1	1	2	C	
Control boxes	6	2	12	Mixed	+X	0	0	1	1	2	C	
Fuel filter housing	3	1	3	Aluminium	-Z	0	0	0	1	1	D	
Fuel pump	4	1	4	Cast iron	+Y	0	1	1	1	3	R	
Piston cooling jets	1	6	6	Polymer	+X	0	0	1	1	2	C	
Inspection plates	2	12	24	Cast iron	-X	1	1	1	1	4	U	
Air cleaner bracket	20	1	20	Cast iron	+Y	1	1	1	1	4	U	

Table 7-4 Remanufacturing facility process information for engine case study (3/5)

	Disassembly				Storage			
Sub-assemblies	Disassembly time (mins)	Labour (hours)	Equip., OHs based on ratio of labour to non-labour	cd*td - Disassembly cost	Approx boxed vol. m^3 of each unit	Preservation req. level (high = 1, medium = 0.5, low = 0)	cph - Preservation cost estimate base of vol.	ch - Storage costs per hour for vol.
Cylinder block	3	0.9	5.625	6.525	0.462	1	9.24	0.004296875
Cylinder head assembly	60	18	112.5	130.5	0.0132	1	1.584	0.000122768
Rocker assembly and injector	25	7.5	46.875	54.375	0.0099	0	1.188	9.20759E-05
Rocker box	5	1.5	9.375	10.875	0.0099	0.5	1.188	9.20759E-05
Rocker covers	15	4.5	28.125	32.625	0.00528	0	0.6336	4.91071E-05
Valve train	25	7.5	46.875	54.375	0.005	0	0.6	4.6503E-05
Connecting rod	30	9	56.25	65.25	0.0036	1	0.432	3.34821E-05
Piston	15	4.5	28.125	32.625	0.00512	1	0.6144	4.7619E-05
Sump	10	3	18.75	21.75	0.239075	0.5	4.7815	0.00222354
Crankshaft	15	4.5	28.125	32.625	0.09375	1	1.875	0.000871931
Main bearings	30	9	56.25	65.25	0.0012	1	0.168	1.11607E-05
Camshaft	10	3	18.75	21.75	0.00375	1	0.075	3.48772E-05
Flywheel	20	6	37.5	43.5	0.03025	1	0.605	0.000281343
Damper	15	4.5	28.125	32.625	0.0128	1	0.256	0.000119048
Air cleaner	10	3	18.75	21.75	0.125	0	5	0.001162574
Exhaust pots	10	3	18.75	21.75	0.0315	1	1.26	0.000292969
Starter motor	5	1.5	9.375	10.875	0.0036	0	0.072	3.34821E-05
Gears	10	3	18.75	21.75	0.02	1	0.4	0.000186012
Gear cover	5	1.5	9.375	10.875	0.054	0.5	1.08	0.000502232
Exhaust manifolds	15	4.5	28.125	32.625	0.0216	1	0.432	0.000200893
Intake manifolds	12	3.6	22.5	26.1	0.06	0.5	1.2	0.000558036
Turbos	10	3	18.75	21.75	0.00324	0	0.1296	3.01339E-05
Water pump	3	0.9	5.625	6.525	0.00225	1	0.045	2.09263E-05
Alternator	5	1.5	9.375	10.875	0.003528	0	0.07056	3.28125E-05
Lifting Brackets	4	1.2	7.5	8.7	0.001458	1	0.05832	1.35603E-05
Flywheel housing	5	1.5	9.375	10.875	0.10125	1	2.025	0.000941685
Oil filter housing	3	0.9	5.625	6.525	0.00128	0.5	0.0768	1.19048E-05
Oil filter header	5	1.5	9.375	10.875	0.0015	0.5	0.03	1.39509E-05
Cooler	3	0.9	5.625	6.525	0.1152	0.5	2.304	0.001071429
Water pipes (multiple)	10	3	18.75	21.75	0.0135	0.5	0.27	0.000125558
Rear plate	5	1.5	9.375	10.875	0.02025	1	0.405	0.000188337
Feet	2	0.6	3.75	4.35	0.012	1	0.48	0.000111607
Oil pipes (multiple)	10	3	18.75	21.75	0.032	0.5	0.64	0.000297619
Fuel pipes (multiple)	10	3	18.75	21.75	0.005	0	0.1	4.6503E-05
Control boxes	10	3	18.75	21.75	0.0075	0	0.3	6.97545E-05
Fuel filter housing	3	0.9	5.625	6.525	0.003	0.5	0.06	2.79018E-05
Fuel pump	5	1.5	9.375	10.875	0.0009	1	0.018	8.37054E-06
Piston cooling jets	12	3.6	22.5	26.1	0.00025	0	0.03	2.32515E-06
Inspection plates	20	6	37.5	43.5	0.000648	1	0.15552	6.02679E-06
Air cleaner bracket	10	3	18.75	21.75	0.0585	1	1.17	0.000544085

Table 7-5 Remanufacturing facility process information for engine case study (4/5)

	Assembly					Reincarnate				
Sub-assemblies	Assembly time (mins)	ta - Assembly time (hours)	Labour (hour)	Equip., OHs based on ratio of labour to non-labour	ca*ta - Assembly cost	Reincarnation time (mins)	tr - Reincarnation time (hours)	Labour	Equip., OHs based on ratio of labour to non-labour	cr*tr - Reincarnation cost
Cylinder block	20	0.333333333	6	37.5	43.5	240	4	72	450	522
Cylinder head assembly	330	5.5	99	618.75	717.75	360	6	108	675	783
Rocker assembly and injector	80	1.333333333	24	150	174	0	0	0	0	0
Rocker box	10	0.166666667	3	18.75	21.75	30	0.5	9	56.25	65.25
Rocker covers	15	0.25	4.5	28.125	32.625	0	0	0	0	0
Valve train	90	1.5	27	168.75	195.75	0	0	0	0	0
Connecting rod	30	0.5	9	56.25	65.25	360	6	108	675	783
Piston	60	1	18	112.5	130.5	720	12	216	1350	1566
Sump	20	0.333333333	6	37.5	43.5	30	0.5	9	56.25	65.25
Crankshaft	15	0.25	4.5	28.125	32.625	480	8	144	900	1044
Main bearings	25	0.416666667	7.5	46.875	54.375	140	2.333333333	42	262.5	304.5
Camshaft	15	0.25	4.5	28.125	32.625	360	6	108	675	783
Flywheel	20	0.333333333	6	37.5	43.5	180	3	54	337.5	391.5
Damper	15	0.25	4.5	28.125	32.625	180	3	54	337.5	391.5
Air cleaner	20	0.333333333	6	37.5	43.5	120	2	36	225	261
Exhaust pots	20	0.333333333	6	37.5	43.5	180	3	54	337.5	391.5
Starter motor	10	0.166666667	3	18.75	21.75	0	0	0	0	0
Gears	80	1.333333333	24	150	174	240	4	72	450	522
Gear cover	10	0.166666667	3	18.75	21.75	45	0.75	13.5	84.375	97.875
Exhaust manifolds	60	1	18	112.5	130.5	120	2	36	225	261
Intake manifolds	60	1	18	112.5	130.5	90	1.5	27	168.75	195.75
Turbos	30	0.5	9	56.25	65.25	90	1.5	27	168.75	195.75
Water pump	10	0.166666667	3	18.75	21.75	30	0.5	9	56.25	65.25
Alternator	20	0.333333333	6	37.5	43.5	0	0	0	0	0
Lifting Brackets	10	0.166666667	3	18.75	21.75	24	0.4	7.2	45	52.2
Flywheel housing	20	0.333333333	6	37.5	43.5	120	2	36	225	261
Oil filter housing	10	0.166666667	3	18.75	21.75	0	0	0	0	0
Oil filter header	15	0.25	4.5	28.125	32.625	90	1.5	27	168.75	195.75
Cooler	15	0.25	4.5	28.125	32.625	120	2	36	225	261
Water pipes (multiple)	20	0.333333333	6	37.5	43.5	120	2	36	225	261
Rear plate	10	0.166666667	3	18.75	21.75	18	0.3	5.4	33.75	39.15
Feet	5	0.083333333	1.5	9.375	10.875	24	0.4	7.2	45	52.2
Oil pipes (multiple)	30	0.5	9	56.25	65.25	0	0	0	0	0
Fuel pipes (multiple)	90	1.5	27	168.75	195.75	0	0	0	0	0
Control boxes	60	1	18	112.5	130.5	0	0	0	0	0
Fuel filter housing	10	0.166666667	3	18.75	21.75	0	0	0	0	0
Fuel pump	10	0.166666667	3	18.75	21.75	45	0.75	13.5	84.375	97.875
Piston cooling jets	25	0.416666667	7.5	46.875	54.375	0	0	0	0	0
Inspection plates	30	0.5	9	56.25	65.25	144	2.4	43.2	270	313.2
Air cleaner bracket	15	0.25	4.5	28.125	32.625	90	1.5	27	168.75	195.75

Table 7-6 Remanufacturing facility process information for engine case study (5/5)

	Reuse					Recycle		Disposal	Purchase	Sales
Sub-assemblies	Reuse prep time (mins)	tu - Reuse time (hours)	Labour	Equip., OHs based on ratio of labour to non-labour	cu*tu - Prep. for reuse cost	cc - Recycling cost	mrc - material sales revenue (recycling)	cdp - disposal costs	cp - Replacement component cost	cru - sale of components directly
Cylinder block	0	0	0	0	0	0.1305	90	120	1500	375
Cylinder head assembly	0	0	0	0	0	2.61	34.2	7.6	1800	450
Rocker assembly and injector	0	0	0	0	0	1.0875	0	0.8	2250	562.5
Rocker box	18	0.3	5.4	33.75	39.15	0.2175	18.45	0.4	225	56.25
Rocker covers	12	0.2	3.6	22.5	26.1	0.6525	0.3	0.2	67.5	16.875
Valve train	0	0	0	0	0	1.0875	42.84	4	112.5	28.125
Connecting rod	0	0	0	0	0	1.305	32.13	3	1350	337.5
Piston	0	0	0	0	0	0.6525	12.852	1.2	1800	450
Sump	20	0.333	6	37.5	43.5	0.435	46.125	6	150	37.5
Crankshaft	0	0	0	0	0	0.6525	53.55	30	2250	562.5
Main bearings	0	0	0	0	0	1.305	6.3	1.2	210	52.5
Camshaft	0	0	0	0	0	0.435	17.85	10	1125	281.25
Flywheel	0	0	0	0	0	0.87	28.56	16	525	131.25
Damper	0	0	0	0	0	0.6525	17.85	10	375	93.75
Air cleaner	15	0.25	4.5	28.125	32.625	0.435	1.5	3	600	150
Exhaust pots	10	0.167	3	18.75	21.75	0.435	14.28	4	225	56.25
Starter motor	5	0.083	1.5	9.375	10.875	0.2175	0	1.2	300	75
Gears	0	0	0	0	0	0.435	17.85	10	375	93.75
Gear cover	15	0.25	4.5	28.125	32.625	0.2175	46.125	6	375	93.75
Exhaust manifolds	20	0.333	6	37.5	43.5	0.6525	3.57	2	225	56.25
Intake manifolds	15	0.25	4.5	28.125	32.625	0.522	15.375	2	187.5	46.875
Turbos	0	0	0	0	0	0.435	4.284	1.2	450	112.5
Water pump	0	0	0	0	0	0.1305	1.05	1.4	187.5	46.875
Alternator	5	0.083	1.5	9.375	10.875	0.2175	0	1.2	262.5	65.625
Lifting Brackets	5	0.083	1.5	9.375	10.875	0.174	2.142	0.6	75	18.75
Flywheel housing	20	0.333	6	37.5	43.5	0.2175	10.5	14	525	131.25
Oil filter housing	0	0	0	0	0	0.1305	9.225	0.4	56.25	14.0625
Oil filter header	10	0.167	3	18.75	21.75	0.2175	6.15	0.8	187.5	46.875
Cooler	15	0.25	4.5	28.125	32.625	0.1305	30.75	4	600	150
Water pipes (multiple)	10	0.167	3	18.75	21.75	0.435	7.6875	1	375	93.75
Rear plate	5	0.083	1.5	9.375	10.875	0.2175	5.355	3	112.5	28.125
Feet	5	0.083	1.5	9.375	10.875	0.087	0.6	0.4	45	11.25
Oil pipes (multiple)	0	0	0	0	0	0.435	7.6875	1	225	56.25
Fuel pipes (multiple)	0	0	0	0	0	0.435	2	0.8	150	37.5
Control boxes	0	0	0	0	0	0.435	0	1.2	600	150
Fuel filter housing	0	0	0	0	0	0.1305	4.6125	0.6	22.5	5.625
Fuel pump	0	0	0	0	0	0.2175	0.6	0.8	450	112.5
Piston cooling jets	0	0	0	0	0	0.522	0.3	0.2	180	45
Inspection plates	12	0.2	3.6	22.5	26.1	0.87	3.6	0.4	180	45
Air cleaner bracket	10	0.167	3	18.75	21.75	0.435	3	4	225	56.25

Table 7-7 Remanufacturing facility process information for DMM validation (1/3)

Sub-assemblies	Part Number	Route	CPR	$CPD = \sum_j (nd_j cd_j td_j (TSsl_j + nsl_j) TQ_1), \quad TQ_1 = 2 - q_i$					$CCS = \sum_j (nh_j (ch_j th_j + cph_j))$			
				CPD					CCS			
				nd	cd*td	TSsl	nsl	Result	nh	ch	cph	Result
Cylinder block	1	R		1	6.525	1.1	0	10.457618	0	0.004296875	9.24	0
Cylinder head assembly	2	R		1	130.5	1.1	0	209.15235	0	0.000122768	1.584	0
Rocker assembly and injector	3	D		1	54.375	0	1	79.224375	0	9.20759E-05	1.188	0
Rocker box	4	U		1	10.875	1.1	0	17.429363	1	9.20759E-05	1.188	1.386884
Rocker covers	5	D		1	32.625	0	1	47.534625	0	4.91071E-05	0.6336	0
Valve train	6	C		1	54.375	0	1	79.224375	0	4.6503E-05	0.6	0
Connecting rod	7	R		1	65.25	1.1	0	104.57618	0	3.34821E-05	0.432	0
Piston	8	C		1	32.625	0	1	47.534625	0	4.7619E-05	0.6144	0
Sump	9	U		1	21.75	1.1	0	34.858725	1	0.00222354	4.7815	9.584346
Crankshaft	10	R		1	32.625	1.1	0	52.288088	0	0.000871931	1.875	0
Main bearings	11	R		1	65.25	1.1	0	104.57618	0	1.11607E-05	0.168	0
Camshaft	12	R		1	21.75	1.1	0	34.858725	0	3.48772E-05	0.075	0
Flywheel	13	C		1	43.5	0	1	63.3795	0	0.000281343	0.605	0
Damper	14	R		1	32.625	1.1	0	52.288088	0	0.000119048	0.256	0
Air cleaner	15	C		1	21.75	0	1	31.68975	0	0.001162574	5	0
Exhaust pots	16	U		1	21.75	1.1	0	34.858725	1	0.000292969	1.26	1.892813
Starter motor	17	C		1	10.875	0	1	15.844875	0	3.34821E-05	0.072	0
Gears	18	C		1	21.75	0	1	31.68975	0	0.000186012	0.4	0
Gear cover	19	U		1	10.875	1.1	0	17.429363	1	0.000502232	1.08	2.164821
Exhaust manifolds	20	C		1	32.625	0	1	47.534625	0	0.000200893	0.432	0
Intake manifolds	21	C		1	26.1	0	1	38.0277	0	0.000558036	1.2	0
Turbos	22	C		1	21.75	0	1	31.68975	0	3.01339E-05	0.1296	0
Water pump	23	C		1	6.525	0	1	9.506925	0	2.09263E-05	0.045	0
Alternator	24	C		1	10.875	0	1	15.844875	0	3.28125E-05	0.07056	0
Lifting Brackets	25	C		1	8.7	0	1	12.6759	0	1.35603E-05	0.05832	0
Flywheel housing	26	U		1	10.875	1.1	0	17.429363	1	0.000941685	2.025	4.05904
Oil filter housing	27	D		1	6.525	0	1	9.506925	0	1.19048E-05	0.0768	0
Oil filter header	28	R		1	10.875	1.1	0	17.429363	0	1.39509E-05	0.03	0
Cooler	29	C		1	6.525	0	1	9.506925	0	0.001071429	2.304	0
Water pipes (multiple)	30	U		1	21.75	1.1	0	34.858725	1	0.000125558	0.27	0.541205
Rear plate	31	U		1	10.875	1.1	0	17.429363	1	0.000188337	0.405	0.811808
Feet	32	U		1	4.35	1.1	0	6.971745	1	0.000111607	0.48	0.721071
Oil pipes (multiple)	33	C		1	21.75	0	1	31.68975	0	0.000297619	0.64	0
Fuel pipes (multiple)	34	C		1	21.75	0	1	31.68975	0	4.6503E-05	0.1	0
Control boxes	35	D		1	21.75	0	1	31.68975	0	6.97545E-05	0.3	0
Fuel filter housing	36	D		1	6.525	0	1	9.506925	0	2.79018E-05	0.06	0
Fuel pump	37	C		1	10.875	0	1	15.844875	0	8.37054E-06	0.018	0
Piston cooling jets	38	C		1	26.1	0	1	38.0277	0	2.32515E-06	0.03	0
Inspection plates	39	U		1	43.5	1.1	0	69.71745	1	6.02679E-06	0.15552	0.168538
Air cleaner bracket	40	U		1	21.75	1.1	0	34.858725	1	0.000544085	1.17	2.345223
Product (engine)			337.8113					1600.3324				23.67575

Table 7-8 Remanufacturing facility process information for DMM validation (2/3)

Part Number	$CCR = ro_{j1} = \sum_j nr_j(TQ_2 cr_j tr_j) + CCP, \quad TQ_2 = 3 - 2q_j$					$CCU = ro_{j2} = \sum_j nu_j(TQ_3 cu_j tu_j(fr_j + fu_j) - cru_j), \quad TQ_3 = 2 - q_j$					
	CCR					CCU					
	nr	cr*tr	cp	CCP	Result	nu	cu*tu	fr	fu	cru	Result
1	1	522	1500	0	999.108	0	0	0	1	375	0
2	1	783	1800	0	1498.662	0	0	0	1	450	0
3	0	0	2250	2250	2250	0	0	0	1	562.5	0
4	0	65.25	225	225	225	1	39.15	0	1	56.25	0.79155
5	0	0	67.5	67.5	67.5	0	26.1	0	1	16.875	0
6	0	0	112.5	112.5	112.5	0	0	0	1	28.125	0
7	1	783	1350	0	1498.662	0	0	0	1	337.5	0
8	0	1566	1800	1800	1800	0	0	0	1	450	0
9	0	65.25	150	150	150	1	43.5	0	1	37.5	25.8795
10	1	1044	2250	0	1998.216	0	0	0	1	562.5	0
11	1	304.5	210	0	582.813	0	0	0	1	52.5	0
12	1	783	1125	0	1498.662	0	0	0	1	281.25	0
13	0	391.5	525	525	525	0	0	0	1	131.25	0
14	1	391.5	375	0	749.331	0	0	0	1	93.75	0
15	0	261	600	600	600	0	32.625	0	1	150	0
16	0	391.5	225	225	225	1	21.75	0	1	56.25	-24.5603
17	0	0	300	300	300	0	10.875	0	1	75	0
18	0	522	375	375	375	0	0	0	1	93.75	0
19	0	97.875	375	375	375	1	32.625	0	1	93.75	-46.2154
20	0	261	225	225	225	0	43.5	0	1	56.25	0
21	0	195.75	187.5	187.5	187.5	0	32.625	0	1	46.875	0
22	0	195.75	450	450	450	0	0	0	1	112.5	0
23	0	65.25	187.5	187.5	187.5	0	0	0	1	46.875	0
24	0	0	262.5	262.5	262.5	0	10.875	0	1	65.625	0
25	0	52.2	75	75	75	0	10.875	0	1	18.75	0
26	0	261	525	525	525	1	43.5	0	1	131.25	-67.8705
27	0	0	56.25	56.25	56.25	0	0	0	1	14.0625	0
28	1	195.75	187.5	0	374.6655	0	21.75	0	1	46.875	0
29	0	261	600	600	600	0	32.625	0	1	150	0
30	0	261	375	375	375	1	21.75	0	1	93.75	-62.0603
31	0	39.15	112.5	112.5	112.5	1	10.875	0	1	28.125	-12.2801
32	0	52.2	45	45	45	1	10.875	0	1	11.25	4.594875
33	0	0	225	225	225	0	0	0	1	56.25	0
34	0	0	150	150	150	0	0	0	1	37.5	0
35	0	0	600	600	600	0	0	0	1	150	0
36	0	0	22.5	22.5	22.5	0	0	0	1	5.625	0
37	0	97.875	450	450	450	0	0	0	1	112.5	0
38	0	0	180	180	180	0	0	0	1	45	0
39	0	313.2	180	180	180	1	26.1	0	1	45	-6.9723
40	0	195.75	225	225	225	1	21.75	0	1	56.25	-24.5603
					21338.87						-213.253

Table 7-9 Remanufacturing facility process information for DMM validation (3/3)

Part Number	$CCC = ro_{j3} = \sum_j nc_j(cc_j - mrc_j)$ CCC				$CCD = ro_{j4} = \sum_j ndp_j cdp_j$ CCD			$CPA = \sum_j na_j ca_j ta_j$ CPA			CPF	CRF
	nc	cc	mrc	Result	nd	cdp	Result	na	ca*ta	Result		
1	0	0.1305	90	0	0	120	0	1	43.5	43.5		
2	0	2.61	34.2	0	0	7.6	0	1	717.75	717.75		
3	0	1.0875	0	0	1	0.8	0.8	1	174	174		
4	0	0.2175	18.45	0	0	0.4	0	1	21.75	21.75		
5	0	0.6525	0.3	0	1	0.2	0.2	1	32.625	32.625		
6	1	1.0875	42.84	-41.7525	0	4	0	1	195.75	195.75		
7	0	1.305	32.13	0	0	3	0	1	65.25	65.25		
8	1	0.6525	12.852	-12.1995	0	1.2	0	1	130.5	130.5		
9	0	0.435	46.125	0	0	6	0	1	43.5	43.5		
10	0	0.6525	53.55	0	0	30	0	1	32.625	32.625		
11	0	1.305	6.3	0	0	1.2	0	1	54.375	54.375		
12	0	0.435	17.85	0	0	10	0	1	32.625	32.625		
13	1	0.87	28.56	-27.69	0	16	0	1	43.5	43.5		
14	0	0.6525	17.85	0	0	10	0	1	32.625	32.625		
15	1	0.435	1.5	-1.065	0	3	0	1	43.5	43.5		
16	0	0.435	14.28	0	0	4	0	1	43.5	43.5		
17	1	0.2175	0	0.2175	0	1.2	0	1	21.75	21.75		
18	1	0.435	17.85	-17.415	0	10	0	1	174	174		
19	0	0.2175	46.125	0	0	6	0	1	21.75	21.75		
20	1	0.6525	3.57	-2.9175	0	2	0	1	130.5	130.5		
21	1	0.522	15.375	-14.853	0	2	0	1	130.5	130.5		
22	1	0.435	4.284	-3.849	0	1.2	0	1	65.25	65.25		
23	1	0.1305	1.05	-0.9195	0	1.4	0	1	21.75	21.75		
24	1	0.2175	0	0.2175	0	1.2	0	1	43.5	43.5		
25	1	0.174	2.142	-1.968	0	0.6	0	1	21.75	21.75		
26	0	0.2175	10.5	0	0	14	0	1	43.5	43.5		
27	0	0.1305	9.225	0	1	0.4	0.4	1	21.75	21.75		
28	0	0.2175	6.15	0	0	0.8	0	1	32.625	32.625		
29	1	0.1305	30.75	-30.6195	0	4	0	1	32.625	32.625		
30	0	0.435	7.6875	0	0	1	0	1	43.5	43.5		
31	0	0.2175	5.355	0	0	3	0	1	21.75	21.75		
32	0	0.087	0.6	0	0	0.4	0	1	10.875	10.875		
33	1	0.435	7.6875	-7.2525	0	1	0	1	65.25	65.25		
34	1	0.435	2	-1.565	0	0.8	0	1	195.75	195.75		
35	0	0.435	0	0	1	1.2	1.2	1	130.5	130.5		
36	0	0.1305	4.6125	0	1	0.6	0.6	1	21.75	21.75		
37	1	0.2175	0.6	-0.3825	0	0.8	0	1	21.75	21.75		
38	1	0.522	0.3	0.222	0	0.2	0	1	54.375	54.375		
39	0	0.87	3.6	0	0	0.4	0	1	65.25	65.25		
40	0	0.435	3	0	0	4	0	1	32.625	32.625		
				-163.792			3.2			3132	3000	**29058.844**

Table 7-10 Predecessors in engine disassembly case study

Sub-assemblies	Part Number	Predecessors
Cylinder block	1	2,3,4,5,6,7,8,9,10,11,12,13,14,15,16,17,18,19,20,21,22,23,24,25,26,27,28,29,30,31,32, 33,34,35,36,37,38,39,40
Cylinder head assembly	2	3,4,5,15,16,20,21,22,27,33,34,35,36
Rocker assembly and injector	3	4,5,34,36
Rocker box	4	5
Rocker covers	5	-
Valve train	6	2,3,4,5,15,16,20,21,22,27,33,34,35,36
Connecting rod	7	9,10,11,13,14,17,25,26
Piston	8	7,9,10,11,13,14,17,25,26
Sump	9	-
Crankshaft	10	9,11,13,14,17,25,26
Main bearings	11	9
Camshaft	12	2,3,4,5,6,14,15,16,18,19,20,21,22,23,27,30,33,34,35,36,37
Flywheel	13	-
Damper	14	-
Air cleaner	15	-
Exhaust pots	16	-
Starter motor	17	-
Gears	18	14,19,23,24,30,34,36,37
Gear cover	19	14,23,24,30,34,36,37
Exhaust manifolds	20	15,16,22
Intake manifolds	21	15,35
Turbos	22	15,16
Water pump	23	30
Alternator	24	-
Lifting Brackets	25	-
Flywheel housing	26	13,17,25
Oil filter housing	27	-
Oil filter header	28	27
Cooler	29	28,30,33
Water pipes (multiple)	30	-
Rear plate	31	14,18,19,23,24,30,32,34,36,37
Feet	32	-
Oil pipes (multiple)	33	27
Fuel pipes (multiple)	34	36
Control boxes	35	-
Fuel filter housing	36	-
Fuel pump	37	34,36
Piston cooling jets	38	-
Inspection plates	39	-
Air cleaner bracket	40	15

Table 7-11 Component interference matrix for engine case study

Part Number	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20	21	22	23	24	25	26	27	28	29	30	31	32	33	34	35	36	37	38	39	40
1	x	1	0	0	0	0	0	1	1	1	1	1	0	0	0	0	0	1	0	0	0	0	1	0	0	1	0	1	1	1	1	0	1	1	0	0	1	1	1	1
2	1	x	1	1	0	1	0	0	0	0	0	0	0	0	0	0	0	0	0	1	1	0	0	0	0	0	0	0	0	0	0	0	1	0	0	0	0	0	0	0
3	0	1	x	1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	1	0	0	0	0	0	0
4	0	1	1	x	1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
5	0	0	0	1	x	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
6	0	1	0	0	0	x	0	0	0	0	0	1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
7	0	0	0	0	0	0	x	1	0	1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
8	1	0	0	0	0	0	1	x	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
9	1	0	0	0	0	0	0	0	x	0	1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
10	1	0	0	0	0	0	1	0	0	x	1	0	1	1	0	0	0	0	0	0	0	0	0	0	0	1	0	0	0	0	0	0	0	0	0	0	0	0	0	0
11	1	0	0	0	0	0	0	0	1	1	x	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
12	1	0	0	0	0	1	0	0	0	0	0	x	0	0	0	0	0	1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
13	0	0	0	0	0	0	0	0	0	1	0	0	x	0	0	0	0	0	0	0	0	0	0	0	0	1	0	0	0	0	0	0	0	0	0	0	0	0	0	0
14	0	0	0	0	0	0	0	0	0	1	0	0	0	x	0	0	0	0	1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
15	0	0	0	0	0	0	0	0	0	0	0	0	0	0	x	0	0	0	0	0	1	1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	1
16	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	x	0	0	0	0	0	1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
17	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	x	0	0	0	0	0	0	0	0	1	0	0	0	0	0	0	0	0	0	0	0	0	0	0
18	1	0	0	0	0	0	0	0	0	0	0	1	0	0	0	0	0	x	1	0	0	0	0	0	0	0	0	0	0	0	1	0	0	0	0	0	0	0	0	0
19	0	0	0	0	0	0	0	0	0	0	0	0	0	1	0	0	0	1	x	0	0	0	1	1	0	0	0	0	0	0	1	0	0	0	0	0	1	0	0	0
20	0	1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	x	0	1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
21	0	1	0	0	0	0	0	0	0	0	0	0	0	0	1	0	0	0	0	0	x	0	0	0	0	0	0	0	0	0	0	0	0	0	1	0	0	0	0	0
22	0	0	0	0	0	0	0	0	0	0	0	0	0	0	1	1	0	0	0	1	0	x	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
23	1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	1	0	0	0	x	0	0	0	0	0	0	1	0	0	0	0	0	0	0	0	0	0
24	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	1	0	0	0	0	x	0	0	0	0	0	0	1	0	0	0	0	0	0	0	0	0
25	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	x	1	0	0	0	0	0	0	0	0	0	0	0	0	0	0
26	1	0	0	0	0	0	0	0	0	1	0	0	1	0	0	0	1	0	0	0	0	0	0	0	1	x	0	0	0	0	0	0	0	0	0	0	0	0	0	0
27	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	x	1	0	0	0	0	1	0	0	0	0	0	0	0
28	1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	1	x	0	0	0	0	0	0	0	0	0	0	0	0
29	1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	x	1	0	0	1	0	0	0	0	0	0	0
30	1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	1	0	0	0	0	0	1	x	0	0	0	0	0	0	0	0	0	0
31	1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	1	1	0	0	0	0	1	0	0	0	0	0	0	x	1	0	0	0	0	0	0	0	0
32	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	1	x	0	0	0	0	0	0	0	0
33	1	1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	1	0	1	0	0	0	x	0	0	0	0	0	0	0
34	1	0	1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	x	0	1	1	0	0	0
35	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	1	0	0	0	0	0	0	0	0	0	0	0	0	0	x	0	0	0	0	0
36	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	1	0	x	0	0	0	0
37	1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	1	0	0	x	0	0	0
38	1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	x	0	0
39	1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	x	0
40	1	0	0	0	0	0	0	0	0	0	0	0	0	0	1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	x

Table 7-12 Dissasembly time matrix

Part Number	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20	21	22	23	24	25	26	27	28	29	30	31	32	33	34	35	36	37	38	39	40	Disassembly time (mins)	Primary removal direction
1	x	60	25	5	15	25	30	15	10	15	30	10	20	15	10	10	5	10	5	15	12	10	3	5	4	5	3	5	3	10	5	2	10	10	10	3	5	12	20	10	3	-
2	3	x	25	5	15	25	30	15	10	15	30	10	20	15	10	10	5	10	5	15	12	10	3	5	4	5	3	5	3	10	5	2	10	10	10	3	5	12	20	10	60	+Z
3	3	60	x	5	15	25	30	15	10	15	30	10	20	15	10	10	5	10	5	15	12	10	3	5	4	5	3	5	3	10	5	2	10	10	10	3	5	12	20	10	25	+Z
4	3	60	25	x	15	25	30	15	10	15	30	10	20	15	10	10	5	10	5	15	12	10	3	5	4	5	3	5	3	10	5	2	10	10	10	3	5	12	20	10	5	+Z
5	3	60	25	5	x	25	30	15	10	15	30	10	20	15	10	10	5	10	5	15	12	10	3	5	4	5	3	5	3	10	5	2	10	10	10	3	5	12	20	10	15	+Z
6	3	60	25	5	15	x	30	15	10	15	30	10	20	15	10	10	5	10	5	15	12	10	3	5	4	5	3	5	3	10	5	2	10	10	10	3	5	12	20	10	25	+Z
7	3	60	25	5	15	25	x	15	10	15	30	10	20	15	10	10	5	10	5	15	12	10	3	5	4	5	3	5	3	10	5	2	10	10	10	3	5	12	20	10	30	+Z
8	3	60	25	5	15	25	30	x	10	15	30	10	20	15	10	10	5	10	5	15	12	10	3	5	4	5	3	5	3	10	5	2	10	10	10	3	5	12	20	10	15	+Z
9	5	62	27	7	17	27	32	17	x	17	32	12	22	17	-12	12	7	12	7	17	14	12	5	7	6	7	5	7	5	12	7	4	12	12	12	5	7	14	22	12	10	-Z
10	5	62	27	7	17	27	32	17	12	x	32	12	22	17	-12	12	7	12	7	17	14	12	5	7	6	7	5	7	5	12	7	4	12	12	12	5	7	14	22	12	15	-Z
11	5	62	27	7	17	27	32	17	12	17	x	12	22	17	-12	12	7	12	7	17	14	12	5	7	6	7	5	7	5	12	7	4	12	12	12	5	7	14	22	12	30	-Z
12	4	61	26	6	16	26	31	16	11	16	31	x	21	16	11	11	6	11	6	16	13	11	4	6	5	6	4	6	4	11	6	3	11	11	11	4	6	13	21	11	10	-Y
13	4	61	26	6	16	26	31	16	11	16	31	11	x	16	11	11	6	11	6	16	13	11	4	6	5	6	4	6	4	11	6	3	11	11	11	4	6	13	21	11	20	+Y
14	4	61	26	6	16	26	31	16	11	16	31	11	21	x	11	11	6	11	6	16	13	11	4	6	5	6	4	6	4	11	6	3	11	11	11	4	6	13	21	11	15	-Y
15	3	60	25	5	15	25	30	15	10	15	30	10	20	15	x	10	5	10	5	15	14	10	3	5	4	5	3	5	3	10	5	2	10	10	10	3	5	12	20	11	10	+Z
16	4	61	26	6	16	26	31	16	11	16	31	11	21	16	11	x	6	11	6	16	13	11	4	6	5	6	4	6	4	11	6	3	11	11	11	4	6	13	21	11	10	-X
17	4	61	26	6	16	26	31	16	11	16	31	11	21	16	11	11	x	11	6	16	13	11	4	6	5	6	4	6	4	11	6	3	11	11	11	4	6	13	21	11	5	-Y
18	4	61	26	6	16	26	31	16	11	16	31	11	21	16	11	11	6	x	6	16	13	11	4	6	5	6	4	6	4	11	6	3	11	11	11	4	6	13	21	11	10	-Y
19	4	61	26	6	16	26	31	16	11	16	31	11	21	16	11	11	6	11	x	16	13	11	4	6	5	6	4	6	4	11	6	3	11	11	11	4	6	13	21	11	5	-Y
20	4	61	26	6	16	26	31	16	11	16	31	11	21	16	11	11	6	11	6	x	13	11	4	6	5	6	4	6	4	11	6	3	11	11	11	4	6	13	21	11	15	-X
21	4	61	26	6	16	26	31	16	11	16	31	11	21	16	11	11	6	11	6	16	x	11	4	6	5	6	4	6	4	11	6	3	11	11	11	4	6	13	21	11	12	+X
22	4	61	26	6	16	26	31	16	11	16	31	11	21	16	11	11	6	11	6	16	13	x	4	6	5	6	4	6	4	11	6	3	11	11	11	4	6	13	21	11	10	-X
23	4	61	26	6	16	26	31	16	11	16	31	11	21	16	11	11	6	11	6	16	13	11	x	6	5	6	4	6	4	11	6	3	11	11	11	4	6	13	21	11	3	+X
24	4	61	26	6	16	26	31	16	11	16	31	11	21	16	11	11	6	11	6	16	13	11	4	x	5	6	4	6	4	11	6	3	11	11	11	4	6	13	21	11	5	+Y
25	3	60	25	5	15	25	30	15	10	15	30	10	20	15	10	10	5	10	5	15	12	10	3	5	x	5	3	5	3	10	5	2	10	10	10	3	5	12	20	10	4	+Z
26	4	61	26	6	16	26	31	16	11	16	31	11	21	16	11	11	6	11	6	16	13	11	4	6	5	x	4	6	4	11	6	3	11	11	11	4	6	13	21	11	5	+Y
27	4	61	26	6	16	26	31	16	11	16	31	11	21	16	11	11	6	11	6	16	13	11	4	6	5	6	x	6	4	11	6	3	11	11	11	4	6	13	21	11	3	+X
28	4	61	26	6	16	26	31	16	11	16	31	11	21	16	11	11	6	11	6	16	13	11	4	6	5	6	4	x	4	11	6	3	11	11	11	4	6	13	21	11	5	+X
29	4	61	26	6	16	26	31	16	11	16	31	11	21	16	11	11	6	11	6	16	13	11	4	6	5	6	4	6	x	11	6	3	11	11	11	4	6	13	21	11	3	+X
30	4	61	26	6	16	26	31	16	11	16	31	11	21	16	11	11	6	11	6	16	13	11	4	6	5	6	4	6	4	x	6	3	11	11	11	4	6	13	21	11	10	+X
31	4	61	26	6	16	26	31	16	11	16	31	11	21	16	11	11	6	11	6	16	13	11	4	6	5	6	4	6	4	11	x	3	11	11	11	4	6	13	21	11	5	-Y
32	4	61	26	6	16	26	31	16	11	16	31	11	21	16	11	11	6	11	6	16	13	11	4	6	5	6	4	6	4	11	6	x	11	11	11	4	6	13	21	11	2	-Y
33	4	61	26	6	16	26	31	16	11	16	31	11	21	16	11	11	6	11	6	16	13	11	4	6	5	6	4	6	4	11	6	3	x	11	11	4	6	13	21	11	10	+X
34	4	61	26	6	16	26	31	16	11	16	31	11	21	16	11	11	6	11	6	16	13	11	4	6	5	6	4	6	4	11	6	3	11	x	11	4	6	13	21	11	10	+X
35	4	61	26	6	16	26	31	16	11	16	31	11	21	16	11	11	6	11	6	16	13	11	4	6	5	6	4	6	4	11	6	3	11	11	x	4	6	13	21	11	10	+X
36	5	62	27	7	17	27	30	17	12	17	32	12	22	17	12	12	7	12	7	17	14	12	5	7	6	7	5	7	5	12	7	4	12	12	12	x	7	14	22	12	3	-Z
37	4	61	26	6	16	26	31	16	11	16	31	11	21	16	11	11	6	11	6	16	13	11	4	6	5	6	4	6	4	11	6	3	11	11	11	4	x	13	21	11	5	+Y
38	4	61	26	6	16	26	31	16	11	16	31	11	21	16	11	11	6	11	6	16	13	11	4	6	5	6	4	6	4	11	6	3	11	11	11	4	6	x	21	11	12	+X
39	4	61	26	6	16	26	31	16	11	16	31	11	21	16	11	11	6	11	6	16	13	11	4	6	5	6	4	6	4	11	6	3	11	11	11	4	6	13	x	11	20	-X
40	4	61	26	6	16	26	31	16	11	16	31	11	21	16	11	11	6	11	6	16	13	11	4	6	5	6	4	6	4	11	6	3	11	11	11	4	6	13	21	x	10	+Y

Table 7-13 Sequence, routings and cost estimates of remanufacturing function (1/44)

Test No.	Quality (q)	Distance (km)	Disassembly sequence (by Part Number)																																									
1	0	0	39	16	27	25	32	5	9	15	13	30	40	22	14	24	17	28	23	35	33	38	26	11	10	36	7	4	29	8	20	21	34	3	2	6	37	19	18	31	12
2	0	100	39	9	15	16	11	24	5	17	30	35	36	32	4	23	25	34	27	38	13	14	26	37	19	10	7	22	20	40	33	21	18	3	28	2	31	8	29	6	12
3	0	200	39	13	9	5	27	28	16	32	24	17	36	4	14	11	15	35	40	33	22	30	34	29	3	20	21	2	38	25	6	23	37	26	19	18	12	31	10	7	8
4	0	300	13	39	32	35	27	9	14	30	11	15	38	21	25	28	40	17	23	24	5	26	16	10	36	7	34	4	22	20	8	3	37	33	29	2	6	19	18	12	31
5	0	400	13	16	27	17	9	14	39	28	35	25	11	15	22	40	21	38	24	26	10	33	30	23	5	29	36	7	8	32	4	20	34	37	19	3	2	6	18	31	12
6	0	500	13	24	36	9	15	30	34	37	25	23	16	40	11	17	5	32	14	39	26	22	10	19	35	20	21	7	8	4	18	38	3	31	27	33	2	28	6	12	29
7	0	600	39	24	32	38	27	9	15	13	25	5	4	30	40	16	11	23	28	35	21	22	17	26	14	10	36	7	33	34	20	37	29	19	8	3	2	18	6	12	31
8	0	700	13	16	5	38	24	32	14	9	15	39	17	11	40	35	21	22	25	4	26	10	27	33	36	7	34	3	8	28	20	37	30	23	2	29	19	18	31	6	12
9	0	800	39	16	14	32	24	9	30	11	25	17	13	23	26	38	35	10	15	22	20	40	21	27	33	5	36	7	34	8	28	4	29	3	37	2	6	19	18	31	12
10	0	900	13	32	14	39	24	25	35	30	9	38	16	23	11	15	5	17	22	36	20	4	40	34	37	26	21	27	28	33	3	19	18	10	7	29	8	31	2	6	12
11	0	1000	39	5	30	17	16	23	14	4	24	13	25	32	38	36	26	9	15	22	11	34	40	37	27	3	35	33	20	21	19	10	28	2	7	29	8	6	18	31	12
12	0	1100	13	9	17	32	36	35	24	16	30	38	11	15	25	23	14	26	39	22	20	27	5	10	7	28	8	40	21	34	4	37	33	29	19	18	3	31	2	6	12
13	0	1200	13	14	38	39	27	16	32	17	9	11	35	24	25	30	23	26	33	10	15	28	22	29	36	7	5	40	34	20	4	21	8	37	19	3	18	2	31	6	12
14	0	1300	13	32	36	39	38	16	17	9	15	34	11	14	27	40	5	37	35	21	24	30	28	25	23	33	22	19	29	18	4	26	10	7	3	31	20	2	8	6	12
15	0	1400	13	32	36	35	5	27	30	4	23	9	24	38	11	15	33	39	40	17	16	21	34	3	25	26	14	28	29	10	7	8	37	22	20	19	18	2	31	6	12
16	0	1500	13	30	9	39	38	27	32	33	23	14	28	17	24	16	11	15	29	40	25	22	26	10	35	36	7	21	20	5	4	8	34	3	37	2	6	19	18	12	31
17	0	1600	39	32	38	5	36	13	17	24	14	30	4	27	9	15	33	23	11	28	40	25	34	37	16	19	29	26	18	31	22	35	3	20	21	10	2	6	12	7	8
18	0	1700	39	30	16	35	32	5	9	15	13	14	36	24	17	25	40	34	37	4	21	11	38	22	26	3	27	20	28	23	19	33	18	10	7	8	29	31	2	6	12
19	0	1800	39	30	9	25	24	17	23	35	32	5	14	4	36	16	38	34	3	13	11	15	26	40	21	37	19	18	27	33	22	10	7	28	31	20	29	8	2	6	12
20	0	1900	13	14	27	32	17	16	33	35	28	9	38	39	30	24	23	25	5	4	11	15	22	20	26	40	21	29	10	36	7	8	34	37	19	18	3	31	2	6	12
21	0	2000	13	5	9	38	32	16	17	24	25	35	27	26	33	11	15	14	10	21	36	7	40	4	22	30	39	23	34	37	8	19	28	29	20	3	2	6	18	12	31
22	0	2100	13	9	15	32	35	40	17	27	30	25	21	26	28	23	24	36	38	39	34	33	11	16	14	22	20	10	37	19	5	29	18	7	31	8	4	3	2	6	12
23	0	2200	39	14	9	15	38	17	32	11	16	35	25	27	5	13	4	40	21	24	33	28	22	30	20	29	26	10	36	7	34	23	3	8	37	2	19	6	18	12	31
24	0	2300	13	16	36	25	24	9	32	5	14	4	11	15	38	39	27	34	30	23	3	22	28	37	33	40	35	19	21	29	18	17	26	10	7	20	31	8	2	6	12
25	0	2400	39	38	17	14	13	16	24	5	32	27	9	15	22	25	28	4	36	26	34	40	11	30	20	37	23	33	3	35	10	7	8	19	21	18	2	29	31	6	12
26	0	2500	13	17	30	23	24	39	16	9	25	38	5	35	36	26	32	4	27	33	14	11	15	28	34	40	22	3	29	10	7	20	21	37	8	2	19	6	18	31	12

Table 7-14 Sequence, routings and cost estimates of remanufacturing function (2/44)

Test No.	Remanufacturing Method (1=Reuse, 2=Reincarnate, 3=Recycle, 4=Disposal)																																									Cost (£)
1	1	1	4	3	1	4	1	3	3	1	1	3	2	3	3	2	3	4	3	3	1	2	2	4	2	1	3	3	3	3	3	4	2	3	3	1	3	1	2	2	34,824
2	1	1	3	1	2	3	4	3	1	4	4	1	1	3	3	3	4	3	3	2	1	3	1	2	2	3	3	1	3	3	3	4	2	2	1	3	3	3	2	2	34,849
3	1	3	1	4	4	2	1	1	3	3	4	1	2	2	3	4	1	3	3	1	3	3	4	3	3	2	3	3	3	3	3	1	1	3	2	1	2	2	3	2	34,865
4	3	1	1	4	4	1	2	1	2	3	3	3	3	2	1	3	3	3	4	1	1	2	4	2	3	1	3	3	3	4	3	3	3	2	3	1	3	2	1	2	34,872
5	3	1	4	3	1	2	1	2	4	3	2	3	3	1	3	3	3	1	2	3	1	3	4	3	4	2	3	1	1	3	3	3	1	4	2	3	3	1	2	2	34,888
6	3	3	4	1	3	1	3	3	3	3	1	1	2	3	4	1	2	1	1	3	2	1	4	3	3	2	3	1	3	3	4	1	4	3	2	2	3	2	3	2	34,912
7	1	3	1	3	4	1	3	3	3	4	1	1	1	1	2	3	2	4	3	3	3	1	2	2	4	2	3	3	3	3	3	1	3	4	2	3	3	2	1	2	34,920
8	3	1	4	3	3	1	2	1	3	1	3	2	1	4	3	3	3	1	1	2	4	3	4	2	3	4	3	2	3	3	1	3	2	3	1	3	1	3	2	2	34,936
9	1	1	2	1	3	1	1	2	3	3	3	3	1	3	4	2	3	3	3	1	3	4	3	4	4	2	3	3	2	1	3	4	3	2	3	1	3	1	2	2	34,951
10	3	1	2	1	3	3	4	1	1	3	1	3	2	3	4	3	3	4	3	1	1	3	3	1	3	4	2	3	4	1	3	2	2	3	3	1	2	3	2	2	34,976
11	1	4	1	3	1	3	2	1	3	3	3	1	3	4	1	1	3	3	2	3	1	3	4	4	4	3	3	3	1	2	2	2	2	3	3	3	3	1	2	2	34,992
12	3	1	3	1	4	4	3	1	1	3	2	3	3	3	2	1	1	3	3	4	4	2	2	2	3	1	3	3	1	3	3	3	1	3	4	1	2	3	2	2	35,008
13	3	2	3	1	4	1	1	3	1	2	4	3	3	1	3	1	3	2	3	2	3	3	4	2	4	1	3	3	1	3	3	3	1	4	3	2	1	3	2	2	35,015
14	3	1	4	1	3	1	3	1	3	3	2	2	4	1	4	3	4	3	3	1	2	3	3	3	3	1	3	3	1	1	2	2	4	1	3	2	3	3	2	2	35,040
15	3	1	4	4	4	4	1	1	3	1	3	3	2	3	3	1	1	3	1	3	3	4	3	1	2	2	3	2	2	3	3	3	3	1	3	2	1	3	2	2	35,056
16	3	1	1	1	3	4	1	3	3	2	2	3	3	1	2	3	3	1	3	3	1	2	4	4	2	3	3	4	1	3	3	4	3	2	3	1	3	2	1	2	35,063
17	1	1	3	4	4	3	3	3	2	1	1	4	1	3	3	3	2	2	1	3	3	3	1	1	3	1	3	1	3	4	4	3	3	2	2	3	2	2	3	2	35,087
18	1	1	1	4	1	4	1	3	3	2	4	3	3	3	1	3	3	1	3	2	3	3	1	4	4	3	2	3	1	3	3	2	2	3	3	1	2	3	2	2	35,103
19	1	1	1	3	3	3	3	4	1	4	2	1	4	1	3	3	4	3	2	3	1	1	3	3	1	3	4	3	3	2	2	2	1	3	3	3	2	3	2	2	35,119
20	3	2	4	1	3	1	3	4	2	1	3	1	1	3	3	3	4	1	2	3	3	3	1	1	3	3	2	4	2	3	3	3	1	3	4	1	2	3	2	2	35,126
21	3	4	1	3	1	1	3	3	3	4	4	1	3	2	3	2	2	3	4	2	1	1	3	1	1	3	3	3	3	1	2	3	3	4	2	3	3	2	1	2	35,142
22	3	1	3	1	4	1	3	4	1	3	3	1	2	3	3	4	3	1	3	3	2	1	2	3	3	2	3	1	4	3	3	2	1	3	1	4	2	3	2	2	35,167
23	1	2	1	3	3	3	1	2	1	4	3	4	4	3	1	1	3	3	3	2	3	1	3	3	1	2	4	2	3	3	4	3	3	2	1	3	3	2	1	2	35,174
24	3	1	4	3	3	1	1	4	2	1	2	3	3	1	4	3	1	3	4	3	2	3	3	1	4	1	3	3	3	3	1	2	2	3	1	3	2	3	2	2	35,199
25	1	3	3	2	3	1	3	4	1	4	1	3	3	3	2	1	4	1	3	1	2	1	3	3	3	3	4	4	2	2	3	1	3	3	2	3	1	3	2	2	35,215
26	3	3	1	3	3	1	1	1	3	3	4	4	4	1	1	1	4	3	2	2	3	2	3	1	3	4	3	2	2	3	3	3	3	2	1	3	3	1	2	2	35,230

Table 7-15 Sequence, routings and cost estimates of remanufacturing function (3/44)

Test No.	Quality (q)	Distance (km)	Disassembly sequence (by Part Number)																																											
27	0	2600	13	24	14	16	35	5	4	30	39	38	27	28	17	23	32	25	9	11	15	33	22	40	26	21	10	36	7	20	8	29	34	37	19	3	18	2	6	12	31
28	0	2700	39	9	38	11	15	35	21	17	27	33	25	40	28	14	30	13	36	23	16	34	32	37	22	26	24	5	20	19	29	4	3	10	18	7	2	31	8	6	12
29	0	2800	39	9	15	14	36	25	13	35	24	34	17	11	26	27	5	33	28	30	29	21	10	23	16	4	22	38	7	8	37	40	3	19	32	18	20	31	2	6	12
30	0	2900	39	17	14	13	9	38	27	28	25	11	15	16	35	5	40	32	30	33	26	29	10	22	36	7	34	4	8	3	23	37	24	21	19	20	2	18	31	6	12
31	0	3000	39	9	15	30	17	14	38	13	35	36	11	40	34	21	23	5	16	32	37	4	24	3	25	26	19	10	27	28	18	7	31	33	22	20	2	29	8	6	12
32	0	3100	39	13	9	15	27	25	32	5	16	30	35	14	24	17	22	38	28	23	36	26	34	40	21	20	37	11	33	10	29	4	3	7	19	18	31	8	2	6	12
33	0	3200	13	32	39	27	16	30	28	23	35	36	24	9	17	25	33	38	14	11	15	34	5	40	22	37	29	26	20	19	4	21	10	7	3	8	2	18	31	6	12
34	0	3300	39	14	30	25	32	9	16	24	13	36	5	4	38	34	27	3	17	28	11	26	10	15	23	40	22	20	7	37	33	19	29	35	21	8	2	6	18	12	31
35	0	3400	13	38	27	9	15	33	24	5	11	28	35	30	25	40	39	14	17	26	23	16	10	36	7	34	21	4	37	19	3	18	29	32	22	31	20	8	2	6	12
36	0	3500	39	24	16	38	9	15	11	32	35	13	17	14	25	21	27	30	28	40	23	26	22	5	10	4	36	7	33	8	29	20	34	3	2	37	6	19	18	12	31
37	0	3600	13	30	14	39	24	35	38	23	9	15	27	5	33	36	16	34	21	11	28	17	37	22	20	4	19	3	2	18	32	25	40	31	26	6	12	10	7	29	8
38	0	3700	39	25	32	9	24	11	27	30	23	14	35	28	13	33	17	29	26	5	38	10	15	16	21	36	7	22	34	8	4	3	20	2	6	37	19	40	18	12	31
39	0	3800	39	36	25	13	14	16	9	27	32	33	38	17	26	11	15	5	24	28	10	40	4	22	35	20	21	7	34	37	30	23	8	29	19	3	2	6	18	31	12
40	0	3900	39	17	38	5	36	16	34	14	13	37	27	4	30	23	3	33	24	9	15	19	25	28	18	29	22	40	26	32	20	31	35	21	11	10	2	7	6	12	8
41	0	4000	13	9	14	36	39	38	30	25	34	32	5	16	35	11	15	23	24	4	17	21	27	3	37	33	26	19	28	29	40	18	22	20	10	7	8	2	6	31	12
42	0	4100	13	9	15	32	14	38	39	25	35	24	16	11	21	27	30	40	23	28	5	33	22	17	29	20	4	26	10	36	7	34	37	3	2	8	6	19	18	31	12
43	0	4200	39	17	27	9	15	30	23	35	21	11	25	38	24	16	5	13	40	33	36	28	32	4	34	29	14	3	26	22	20	10	37	7	19	8	2	6	18	31	12
44	0	4300	39	35	17	36	34	32	13	14	37	9	15	5	25	24	4	21	16	38	11	26	22	20	10	3	27	33	7	30	2	28	8	23	6	19	29	18	40	31	12
45	0	4400	39	5	38	35	13	27	4	14	16	9	32	28	33	11	15	25	22	30	23	21	17	24	20	40	26	10	36	7	8	29	34	37	19	18	3	2	31	6	12
46	0	4500	13	5	38	35	32	4	30	27	33	28	24	17	9	15	25	26	39	16	23	29	22	14	21	40	20	11	10	36	7	34	37	8	3	2	6	19	18	12	31
47	0	4600	13	27	36	28	24	39	9	15	38	30	40	16	34	37	11	23	32	35	21	5	33	14	4	29	22	25	3	17	26	10	19	7	18	31	20	8	2	6	12
48	0	4700	39	30	38	13	5	16	14	35	27	17	32	25	9	15	24	40	4	11	26	23	10	36	7	34	8	28	3	33	22	21	29	37	19	20	2	18	6	12	31
49	0	4800	39	24	13	35	5	14	16	30	17	9	15	23	11	27	40	32	25	38	26	28	21	10	22	20	36	7	34	8	33	29	4	37	19	18	31	3	2	6	12
50	0	4900	13	9	15	5	39	36	30	34	11	40	37	17	14	27	25	33	24	26	38	23	16	10	4	22	20	35	28	32	7	3	29	8	21	19	18	2	6	31	12
51	0	5000	13	17	25	9	32	11	27	5	16	14	28	24	39	26	4	10	15	35	36	7	40	38	8	21	33	22	34	20	37	30	29	3	2	23	6	19	18	31	12

Table 7-16 Sequence, routings and cost estimates of remanufacturing function (4/44)

Test No.	Remanufacturing Method (1=Reuse, 2=Reincarnate, 3=Recycle, 4=Disposal)																																											Cost (£)
27	3	3	2	1	4	4	1	1	1	3	4	2	3	3	1	3	1	2	3	3	3	1	1	3	2	4	2	3	3	3	3	3	1	4	3	2	3	2	1	2	35,238
28	1	1	3	2	3	4	3	3	4	3	3	1	2	2	1	3	4	3	1	3	1	3	3	1	3	4	3	1	3	1	4	2	3	2	2	1	3	3	2	2	35,262
29	1	1	3	2	4	3	3	4	3	3	3	2	1	4	4	3	2	1	3	3	2	3	1	1	3	3	2	3	3	1	4	1	1	3	3	1	2	3	2	2	35,278
30	1	3	2	3	1	3	4	2	3	2	3	1	4	4	1	1	1	3	1	3	2	3	4	2	3	1	3	4	3	3	3	3	1	3	2	3	1	3	2	2	35,285
31	1	1	3	1	3	2	3	3	4	4	2	1	3	3	3	4	1	1	3	1	3	4	3	1	1	2	4	2	3	2	1	3	3	3	2	3	3	3	2	2	35,310
32	1	3	1	3	4	3	1	4	1	1	4	2	3	3	3	3	2	3	4	1	3	1	3	3	3	2	3	2	3	1	4	2	1	3	1	3	2	3	2	2	35,326
33	3	1	1	4	1	1	2	3	4	4	3	1	3	3	3	3	2	2	3	3	4	1	3	3	3	1	3	1	1	3	2	2	4	3	2	3	1	3	2	2	35,342
34	1	2	1	3	1	1	1	3	3	4	4	1	3	3	4	4	3	2	2	1	2	3	3	1	3	3	2	3	3	1	3	4	3	3	2	3	3	2	1	2	35,358
35	3	3	4	1	3	3	3	4	2	2	4	1	3	1	1	2	3	1	3	1	2	4	2	3	3	1	3	1	4	3	3	1	3	1	3	3	2	3	2	2	35,365
36	1	3	1	3	1	3	2	1	4	3	3	2	3	3	4	1	2	1	3	1	3	4	2	1	4	2	3	3	3	3	3	4	2	3	3	1	3	2	1	2	35,381
37	3	1	2	1	3	4	3	3	1	3	4	4	3	4	1	3	3	2	2	3	3	3	3	1	1	4	2	3	1	3	1	1	1	3	2	2	2	3	3	2	35,405
38	1	3	1	1	3	2	4	1	3	2	4	2	3	3	3	3	1	4	3	2	3	1	3	4	2	3	3	3	1	4	3	2	3	3	1	1	3	2	1	2	35,413
39	1	4	3	3	2	1	1	4	1	3	3	3	1	2	3	4	3	2	2	1	1	3	4	3	3	2	3	3	1	3	3	3	1	4	2	3	3	1	2	2	35,437
40	1	3	3	4	4	1	3	2	3	3	4	1	1	3	4	3	3	1	3	1	3	2	3	3	3	1	1	1	3	1	4	3	2	2	2	2	3	2	3	2	35,453
41	3	1	2	4	1	3	1	3	3	1	4	1	4	2	3	3	3	1	3	3	4	4	3	3	1	1	2	3	1	3	3	3	2	2	3	2	3	1	2	2	35,469
42	3	1	3	1	2	3	1	3	4	3	1	2	3	4	1	1	3	2	4	3	3	3	3	3	1	1	2	4	2	3	3	4	2	3	3	1	3	1	2	2	35,476
43	1	3	4	1	3	1	3	4	3	2	3	3	3	1	4	3	1	3	4	2	1	1	3	3	2	4	1	3	3	2	3	2	1	3	2	3	3	1	2	2	35,501
44	1	4	3	4	3	1	3	2	3	1	3	4	3	3	1	3	1	3	2	1	3	3	2	4	4	3	2	1	2	2	3	3	3	1	3	3	1	1	2	2	35,517
45	1	4	3	4	3	4	1	2	1	1	1	2	3	2	3	3	3	1	3	3	3	3	3	1	1	2	4	2	3	3	3	3	1	3	4	2	1	3	2	2	35,524
46	3	4	3	4	1	1	1	4	3	2	3	3	1	3	3	1	1	1	3	3	3	2	3	1	3	2	2	4	2	3	3	3	4	2	3	1	3	2	1	2	35,540
47	3	4	4	2	3	1	1	3	3	1	1	1	3	3	2	3	1	4	3	4	3	2	1	3	3	3	4	3	1	2	1	2	3	1	3	3	2	3	2	2	35,564
48	1	1	3	3	4	1	2	4	4	3	1	3	1	3	3	1	1	2	1	3	2	4	2	3	3	2	4	3	3	3	3	3	1	3	2	3	3	2	1	2	35,572
49	1	3	3	4	4	2	1	1	3	1	3	3	2	4	1	1	3	3	1	2	3	2	3	3	4	2	3	3	3	3	1	3	1	3	1	4	2	3	2	2	35,587
50	3	1	3	4	1	4	1	3	2	1	3	3	2	4	3	3	3	1	3	3	1	2	1	3	3	4	2	1	2	4	3	3	3	1	3	2	3	1	2	2	35,612
51	3	3	3	1	1	2	4	4	1	2	2	3	1	1	1	2	3	4	4	2	1	3	3	3	3	3	3	3	3	1	3	4	2	3	3	1	3	1	2	2	35,619

Table 7-17 Sequence, routings and cost estimates of remanufacturing function (5/44)

Test No.	Quality (q)	Distance (km)	Disassembly sequence (by Part Number)																																										
52	0.1	0	39	30	9	15	35	5	17	14	4	27	16	40	11	36	32	13	23	22	28	33	20	24	21	34	3	38	2	25	26	6	29	10	37	19	7	18	31	12	8
53	0.1	100	39	5	25	38	13	17	4	32	30	36	9	34	11	15	3	35	14	16	26	27	33	22	37	40	10	21	28	29	7	23	8	20	2	6	24	19	18	31	12
54	0.1	200	13	5	25	9	32	30	39	27	24	28	14	4	35	33	11	15	17	21	26	40	16	23	38	10	36	7	29	22	8	20	34	3	2	6	37	19	18	31	12
55	0.1	300	13	27	39	33	38	9	15	14	24	5	30	40	32	35	16	17	36	25	34	26	21	23	22	4	11	20	3	37	19	2	10	18	6	28	12	7	29	8	31
56	0.1	400	13	35	25	27	38	39	17	5	26	24	4	32	9	15	11	16	28	14	40	33	21	30	29	23	10	36	7	22	34	37	3	19	20	18	31	8	2	6	12
57	0.1	500	13	24	38	39	30	16	36	25	27	28	23	35	34	9	11	15	17	33	14	32	37	21	40	29	22	26	5	10	4	20	19	3	2	7	8	18	31	6	12
58	0.1	600	13	30	17	35	25	32	24	27	9	38	11	14	26	39	16	23	10	15	33	21	28	22	36	7	34	20	40	29	8	5	4	3	2	37	6	19	18	12	31
59	0.1	700	39	5	38	17	35	32	16	4	9	24	13	14	11	15	27	30	21	23	33	22	25	26	10	20	28	36	7	29	8	40	34	3	2	6	37	19	18	12	31
60	0.1	800	13	17	36	25	24	9	11	15	38	32	40	35	21	16	39	14	5	22	27	30	34	20	28	33	23	4	26	3	29	10	37	2	7	8	6	19	18	12	31
61	0.1	900	13	32	36	16	9	15	24	40	14	27	25	35	30	22	23	34	17	26	21	5	33	38	39	37	20	11	28	10	19	7	8	29	18	31	4	3	2	6	12
62	0.1	1000	13	5	14	16	27	24	30	28	35	39	23	9	32	38	33	25	11	15	17	21	26	10	4	29	36	7	22	40	34	8	20	37	19	3	18	2	31	6	12
63	0.1	1100	13	14	24	35	9	36	27	11	33	25	17	5	34	37	32	39	16	38	4	3	26	28	30	29	10	15	23	22	40	7	19	8	21	20	2	18	6	12	31
64	0.1	1200	39	30	14	36	34	38	27	23	16	25	9	15	5	24	37	13	33	17	35	28	11	32	19	18	29	26	21	22	40	31	20	4	3	2	10	6	12	7	8
65	0.1	1300	13	9	15	30	27	16	5	35	23	11	25	33	38	32	36	21	17	22	20	24	39	4	26	34	28	40	14	3	29	2	10	6	7	37	8	19	18	31	12
66	0.1	1400	39	13	38	14	24	30	36	17	5	35	9	15	32	21	25	40	4	34	27	37	11	3	26	23	33	19	28	29	18	10	7	8	31	16	22	20	2	6	12
67	0.1	1500	39	16	27	32	5	38	36	4	33	13	30	24	9	15	28	25	40	17	22	26	35	34	21	11	29	14	20	10	37	7	8	3	2	6	23	19	18	12	31
68	0.1	1600	39	17	27	30	13	38	23	25	36	16	34	9	32	37	26	11	15	24	40	33	14	28	19	35	29	21	18	31	10	7	8	5	22	4	20	3	2	6	12
69	0.1	1700	13	16	32	25	9	15	36	14	34	39	11	5	4	22	30	17	23	3	40	26	24	37	10	7	19	27	20	28	35	21	33	2	6	18	12	31	8	29	38
70	0.1	1800	13	14	5	39	24	35	25	16	9	11	15	38	36	30	4	22	40	23	32	27	34	33	21	17	3	37	20	26	19	2	6	10	28	7	18	31	12	29	8
71	0.1	1900	13	30	27	17	39	25	26	16	36	28	23	35	32	9	11	15	14	34	33	38	37	21	22	5	4	24	20	19	18	29	3	2	40	31	10	7	8	6	12
72	0.1	2000	39	17	14	38	5	16	32	25	4	9	15	13	27	40	26	28	11	30	24	10	23	22	36	20	35	21	33	34	7	37	19	29	3	18	8	31	2	6	12
73	0.1	2100	13	38	30	25	14	27	33	28	32	16	35	24	23	9	36	17	34	11	15	22	37	20	39	26	40	29	21	5	10	4	3	7	8	19	18	31	2	6	12
74	0.1	2200	39	17	14	35	32	9	15	30	36	40	16	38	34	5	37	25	21	22	23	27	11	24	13	19	33	4	28	18	29	20	3	2	26	6	10	7	8	12	31
75	0.1	2300	13	24	14	5	39	38	35	9	15	36	16	21	32	22	34	37	25	4	17	26	3	30	23	27	40	11	10	20	19	33	28	2	7	6	29	8	18	12	31
76	0.1	2400	13	27	32	9	15	30	23	35	16	17	38	39	33	14	22	20	24	36	34	21	37	5	11	4	3	19	18	2	25	28	40	29	31	6	26	10	7	12	8
77	0.1	2500	39	27	25	9	32	24	16	35	38	14	36	28	34	11	15	33	13	22	37	30	17	29	26	5	20	4	23	10	7	19	8	3	18	31	21	40	2	6	12

Table 7-18 Sequence, routings and cost estimates of remanufacturing function (6/44)

Test No.	Remanufacturing Method (1=Reuse, 2=Reincarnate, 3=Recycle, 4=Disposal)																																										Cost (£)
52	1	1	1	3	4	4	3	2	1	4	1	1	2	4	1	3	3	3	2	3	3	3	3	3	4	3	2	3	1	3	3	2	3	1	2	3	1	2	3	2	33,742
53	1	4	3	3	3	3	1	1	1	4	1	3	2	3	4	4	2	1	1	4	3	3	3	1	2	3	2	3	2	3	3	3	2	3	3	1	3	1	2	2	33,758
54	3	4	3	1	1	1	1	4	3	2	2	1	4	3	2	3	3	3	1	1	1	3	3	2	4	2	3	3	3	3	3	4	2	3	3	1	3	1	2	2	33,766
55	3	4	1	3	3	1	3	2	3	4	1	1	1	4	1	3	4	3	3	1	3	3	3	1	2	3	4	3	1	2	2	3	3	2	2	2	3	3	1	2	33,790
56	3	4	3	4	3	1	3	4	1	3	1	1	1	3	2	1	2	2	1	3	3	1	3	3	2	4	2	3	3	3	4	1	3	3	1	3	2	3	2	2	33,798
57	3	3	3	1	1	1	4	3	4	2	3	4	3	1	2	3	3	3	2	1	3	3	1	3	3	1	4	2	1	3	1	4	2	2	3	3	1	3	2	2	33,822
58	3	1	3	4	3	1	3	4	1	3	2	2	1	1	1	3	2	3	3	3	2	3	4	2	3	3	1	3	3	4	1	4	2	3	3	1	3	2	1	2	33,829
59	1	4	3	3	4	1	1	1	1	3	3	2	2	3	4	1	3	3	3	3	3	1	2	3	2	4	2	3	3	1	3	4	2	3	3	1	3	2	1	2	33,845
60	3	3	4	3	3	1	2	3	3	1	1	4	3	1	1	2	4	3	4	1	3	3	2	3	3	1	1	4	3	2	3	2	2	3	3	1	3	2	1	2	33,869
61	3	1	4	1	1	3	3	1	2	4	3	4	1	3	3	3	3	1	3	4	3	3	1	3	3	2	2	2	1	2	3	3	3	1	1	4	2	3	2	2	33,885
62	3	4	2	1	4	3	1	2	4	1	3	1	1	3	3	3	2	3	3	3	1	2	1	3	4	2	3	1	3	3	3	3	1	4	3	2	1	3	2	2	33,893
63	3	2	3	4	1	4	4	2	3	3	3	4	3	3	1	1	1	3	1	4	1	2	1	3	2	3	3	3	1	2	1	3	3	3	2	3	3	2	1	2	33,917
64	1	1	2	4	3	3	4	3	1	3	1	3	4	3	3	3	3	3	4	2	2	1	1	3	3	1	3	3	1	1	3	1	4	2	2	3	2	2	3	2	33,933
65	3	1	3	1	4	1	4	4	3	2	3	3	3	1	4	3	3	3	3	3	1	1	1	3	2	1	2	4	3	2	2	3	2	3	3	1	3	1	2	2	33,949
66	1	3	3	2	3	1	4	3	4	4	1	3	1	3	3	1	1	3	4	3	2	4	1	3	3	1	2	3	3	2	2	3	1	1	3	3	2	3	2	2	33,965
67	1	1	4	1	4	3	4	1	3	3	1	3	1	3	2	3	1	3	3	1	4	3	3	2	3	2	3	2	3	2	3	4	2	3	3	1	3	2	1	2	33,981
68	1	3	4	1	3	3	3	3	4	1	3	1	1	3	1	2	3	3	1	3	2	2	1	4	3	3	3	1	2	2	3	4	3	1	3	4	2	3	2	2	33,997
69	3	1	1	3	1	3	4	2	3	1	2	4	1	3	1	3	3	4	1	1	3	3	2	2	1	4	3	2	4	3	3	2	3	3	2	1	3	3	3	2	34,012
70	3	2	4	1	3	4	3	1	1	2	3	3	4	1	1	3	1	3	1	4	3	3	3	3	4	3	3	1	1	2	3	2	2	2	3	1	2	3	3	2	34,028
71	3	1	4	3	1	3	1	1	4	2	3	4	1	1	2	3	2	3	3	3	3	3	3	4	1	3	3	1	3	3	4	2	1	1	2	2	3	3	2	2	34,044
72	1	3	2	3	4	1	1	3	1	1	3	3	4	1	1	2	2	1	3	2	3	3	4	3	4	3	3	3	2	3	1	3	4	3	3	1	2	3	2	2	34,060
73	3	3	1	3	2	4	3	2	1	1	4	3	3	1	4	3	3	2	3	3	3	3	1	1	1	3	3	4	2	1	4	2	3	1	3	1	2	3	2	2	34,076
74	1	3	2	4	1	1	3	1	4	1	1	3	3	4	3	3	3	3	3	4	2	3	3	1	3	1	2	3	3	3	4	2	1	3	2	2	3	2	1	2	34,092
75	3	3	2	4	1	3	4	1	3	4	1	3	1	3	3	3	3	1	3	1	4	1	3	4	1	2	2	3	1	3	2	2	2	3	3	3	3	2	1	2	34,108
76	3	4	1	1	3	1	3	4	1	3	3	1	3	2	3	3	3	4	3	3	3	4	2	1	4	1	3	2	3	2	1	3	1	3	1	2	2	2	3	2	34,124
77	1	4	3	1	1	3	1	4	3	2	4	2	3	2	3	3	3	3	3	1	3	3	1	4	3	1	3	2	2	1	3	4	3	1	3	1	2	3	2	2	34,140

Table 7-19 Sequence, routings and cost estimates of remanufacturing function (7/44)

3

Test No.	Quality (q)	Distance (km)	Disassembly sequence (by Part Number)																																									
78	0.1	2600	39	30	16	14	17	38	32	13	24	9	15	11	5	22	25	35	20	40	23	27	26	28	33	21	10	29	36	7	8	34	4	3	2	37	19	18	31	6	12
79	0.1	2700	39	5	32	14	35	16	13	25	17	9	15	4	30	26	11	27	23	28	10	24	36	7	38	8	33	29	22	20	34	37	3	21	2	40	19	18	31	6	12
80	0.1	2800	39	5	14	27	28	30	38	9	15	32	13	16	17	25	4	26	33	24	23	11	22	35	10	36	7	29	8	20	21	40	34	3	37	2	19	6	18	12	31
81	0.1	2900	39	30	9	38	11	15	5	23	24	35	16	27	17	40	36	4	33	13	34	37	25	21	32	26	14	28	10	22	20	3	29	7	2	6	8	19	18	31	12
82	0.1	3000	13	39	24	32	30	17	9	11	15	23	14	27	25	26	40	28	10	33	35	16	5	36	7	8	38	21	29	22	20	4	34	37	3	19	18	31	2	6	12
83	0.1	3100	39	36	5	9	15	16	22	35	34	4	30	21	17	40	20	14	38	32	13	27	24	23	3	33	25	2	11	6	28	37	29	26	10	7	19	18	8	12	31
84	0.1	3200	13	16	9	15	32	38	39	5	24	22	4	36	11	14	34	25	40	27	35	17	33	37	30	28	23	29	20	3	26	10	19	7	21	8	2	18	6	31	12
85	0.1	3300	39	38	36	24	16	27	5	33	34	35	17	4	37	3	32	30	25	28	29	23	13	9	26	11	15	22	14	40	10	7	19	18	20	31	21	8	2	6	12
86	0.1	3400	13	30	32	16	24	17	39	35	14	23	36	9	15	22	20	38	27	40	34	11	28	33	25	21	29	5	37	19	26	10	7	18	31	8	4	3	2	6	12
87	0.1	3500	13	27	16	14	39	33	36	32	34	25	28	5	38	24	9	37	4	30	3	17	35	26	23	29	11	15	19	18	10	40	31	21	7	8	22	20	2	6	12
88	0.1	3600	13	30	5	38	17	4	9	24	14	35	16	32	25	11	15	27	39	26	21	10	22	33	28	29	20	23	36	7	34	37	40	8	19	18	3	31	2	6	12
89	0.1	3700	39	14	27	24	5	38	28	4	9	15	25	40	33	11	30	32	13	17	23	26	16	29	22	10	36	7	8	20	35	34	37	3	21	2	19	18	6	12	31
90	0.1	3800	39	27	13	35	16	30	36	17	9	38	23	11	25	32	33	24	14	28	26	34	29	5	4	10	15	7	3	21	8	37	40	19	18	22	20	2	31	6	12
91	0.1	3900	13	36	38	27	34	28	33	35	5	17	14	30	25	29	4	39	9	15	24	21	40	26	37	11	3	10	23	7	8	16	22	19	20	2	18	32	31	6	12
92	0.1	4000	13	32	36	39	9	15	11	35	17	5	16	30	38	21	40	34	14	4	23	22	24	37	19	27	18	3	28	20	33	31	29	25	2	6	26	12	10	7	8
93	0.1	4100	39	30	36	27	35	23	28	5	9	32	38	14	33	17	4	11	34	24	25	3	29	13	37	26	10	15	16	21	19	40	22	18	31	20	2	7	6	8	12
94	0.1	4200	13	38	16	25	9	15	11	36	17	30	23	5	39	4	40	35	14	22	21	20	24	27	34	3	26	33	32	10	7	8	28	2	6	29	37	19	18	31	12
95	0.1	4300	13	5	35	9	14	39	36	11	15	30	4	38	27	24	17	33	23	25	16	22	34	37	3	21	32	26	19	28	10	20	18	2	6	7	40	29	31	8	12
96	0.1	4400	39	30	32	24	14	5	35	23	25	38	13	17	26	16	9	27	11	15	10	21	22	4	33	36	7	40	28	20	34	29	3	2	37	19	18	31	6	8	12
97	0.1	4500	13	38	32	35	16	5	39	17	14	30	24	27	9	15	33	40	22	11	4	20	21	28	25	26	10	36	7	29	34	3	37	23	19	18	31	8	2	6	12
98	0.1	4600	39	25	32	24	35	16	38	36	17	34	27	9	37	11	33	13	26	14	10	15	7	21	28	8	5	4	40	22	30	29	3	23	20	19	2	6	18	31	12
99	0.1	4700	13	14	9	39	25	11	5	35	17	26	4	16	38	10	15	36	7	30	40	22	23	20	27	21	33	8	32	24	34	3	2	28	6	29	37	19	18	12	31
100	0.1	4800	13	39	9	15	14	24	30	35	21	16	5	4	23	36	38	27	34	22	17	40	25	32	37	19	20	33	3	28	18	11	29	26	2	10	6	7	12	8	31
101	0.1	4900	13	32	16	30	35	14	39	36	27	28	24	17	5	34	9	11	15	23	21	33	40	38	37	29	4	25	22	19	26	3	20	18	10	2	7	6	8	31	12
102	0.1	5000	39	27	9	32	17	13	16	35	11	15	25	26	21	14	22	28	40	5	33	20	30	10	36	7	23	38	29	34	37	4	24	8	3	2	6	19	18	31	12

Table 7-20 Sequence, routings and cost estimates of remanufacturing function (8/44)

Test No.	Remanufacturing Method (1=Reuse, 2=Reincarnate, 3=Recycle, 4=Disposal)																																										Cost (£)
78	1	1	1	2	3	3	1	3	3	1	3	2	4	3	3	4	3	1	3	4	1	2	3	3	2	3	4	2	3	3	1	4	2	3	1	3	1	3	2	2	34,147
79	1	4	1	2	4	1	3	3	3	1	3	1	1	1	2	4	3	2	2	3	4	2	3	3	3	3	3	3	3	3	4	3	2	1	1	3	1	3	2	2	34,163
80	1	4	2	4	2	1	3	1	3	1	3	1	3	3	1	1	3	3	3	2	3	4	2	4	2	3	3	3	3	1	3	4	3	2	1	3	3	2	1	2	34,179
81	1	1	1	3	2	3	4	3	3	4	1	4	3	1	4	1	3	3	3	3	3	3	1	1	2	2	2	3	3	4	3	2	2	3	3	1	3	1	2	2	34,203
82	3	1	3	1	1	3	1	2	3	3	2	4	3	1	1	2	2	3	4	1	4	4	2	3	3	3	3	3	3	1	3	3	4	1	3	1	2	3	2	2	34,211
83	1	4	4	1	3	1	3	4	3	1	1	3	3	1	3	2	3	1	3	4	3	3	4	3	3	2	2	3	2	3	3	1	2	2	1	3	3	2	1	2	34,235
84	3	1	1	3	1	3	1	4	3	3	1	4	2	2	3	3	1	4	4	3	3	3	1	2	3	3	3	4	1	2	1	2	3	3	2	3	3	1	2	2	34,251
85	1	3	4	3	1	4	4	3	3	4	3	1	3	4	1	1	3	2	3	3	3	1	1	2	3	3	2	1	2	2	1	3	3	1	3	3	2	3	2	2	34,267
86	3	1	1	1	3	3	1	4	2	3	4	1	3	3	3	3	4	1	3	2	2	3	3	3	3	4	3	1	1	2	2	3	1	3	1	4	2	3	2	2	34,283
87	3	4	1	2	1	3	4	1	3	3	2	4	3	3	1	3	1	1	4	3	4	1	3	3	2	3	1	3	2	1	1	3	2	3	3	3	2	3	2	2	34,299
88	3	1	4	3	3	1	1	3	2	4	1	1	3	2	3	4	1	1	3	2	3	3	2	3	3	3	4	2	3	3	1	3	1	3	4	1	2	3	2	2	34,306
89	1	2	4	3	4	3	2	1	1	3	3	1	3	2	1	1	3	3	3	1	1	3	3	2	4	2	3	3	4	3	3	4	3	2	1	3	3	2	1	2	34,322
90	1	4	3	4	1	1	4	3	1	3	3	2	3	1	3	3	2	2	1	3	3	4	1	2	3	2	4	3	3	3	1	1	3	3	3	2	1	3	2	2	34,346
91	3	4	3	4	3	2	3	4	4	3	2	1	3	3	1	1	1	3	3	3	1	1	3	2	4	2	3	2	3	1	3	1	3	2	3	1	1	3	2	2	34,362
92	3	1	4	1	1	3	2	4	3	4	1	1	3	3	1	3	2	1	3	3	3	3	1	4	3	4	2	3	3	1	3	3	2	3	1	2	2	2	3	2	34,378
93	1	1	4	4	4	3	2	4	1	1	3	2	3	3	1	2	3	3	3	4	3	3	3	1	2	3	1	3	1	1	3	3	1	3	2	2	3	3	2	2	34,394
94	3	3	1	3	1	3	2	4	3	1	3	4	1	1	1	4	2	3	3	3	3	4	3	4	1	3	1	2	2	3	2	2	3	3	3	1	3	1	2	2	34,410
95	3	4	4	1	2	1	4	2	3	1	1	3	4	3	3	3	3	3	1	3	3	3	4	3	1	1	1	2	2	3	3	2	3	2	1	3	1	3	2	2	34,426
96	1	1	1	3	2	4	4	3	3	3	3	3	1	1	1	4	2	3	2	3	3	1	3	4	2	1	2	3	3	3	4	2	3	1	3	1	3	3	2	2	34,434
97	3	3	1	4	1	4	1	3	2	1	3	4	1	3	3	1	3	2	1	3	3	2	3	1	2	4	2	3	3	4	3	3	1	3	1	3	2	3	2	2	34,449
98	1	3	1	3	4	1	3	4	3	3	4	1	3	2	3	3	1	2	2	3	2	3	2	3	4	1	1	3	1	3	4	3	3	1	2	3	3	1	2	2	34,474
99	3	2	1	1	3	2	4	4	3	1	1	1	3	2	3	4	2	1	1	3	3	3	4	3	3	3	1	3	3	4	2	2	3	3	3	1	3	2	1	2	34,481
100	3	1	1	3	2	3	1	4	3	1	4	1	3	4	3	4	3	3	3	1	3	1	3	1	3	3	4	2	3	2	3	1	2	2	3	2	2	3	1	2	34,505
101	3	1	1	1	4	2	1	4	4	2	3	3	4	3	1	2	3	3	3	3	1	3	3	3	1	3	3	1	1	4	3	3	2	2	2	3	3	1	2	2	34,521
102	1	4	1	1	3	3	1	4	2	3	3	1	3	2	3	2	1	4	3	3	1	2	4	2	3	3	3	3	3	1	3	3	4	2	3	1	3	1	2	2	34,529

Table 7-21 Sequence, routings and cost estimates of remanufacturing function (9/44)

Test No.	Quality (q)	Distance (km)	Disassembly sequence (by Part Number)																																										
103	0.2	0	13	36	16	14	25	34	9	15	24	37	32	39	22	5	30	4	27	28	3	17	35	40	21	23	38	20	33	11	19	18	29	2	6	26	31	10	7	12	8				
104	0.2	100	39	25	24	30	14	35	17	16	13	9	15	26	32	27	22	36	21	23	11	33	10	5	28	34	7	37	40	4	8	19	29	38	3	20	2	18	31	6	12				
105	0.2	200	39	16	36	32	25	30	5	13	9	35	14	4	34	11	15	17	21	22	37	3	24	40	38	27	26	33	28	10	23	19	18	29	7	31	20	2	8	6	12				
106	0.2	300	13	5	30	23	9	15	4	24	39	27	36	16	22	17	11	38	20	35	14	28	40	32	33	25	34	3	29	21	26	37	19	18	2	31	10	7	8	6	12				
107	0.2	400	13	25	35	32	14	17	24	5	4	39	30	16	38	9	15	23	27	33	36	21	34	37	11	26	22	20	19	10	28	3	18	7	2	31	40	6	8	29	12				
108	0.2	500	39	38	9	25	30	35	17	24	16	11	27	13	28	5	26	4	33	23	29	32	14	10	15	36	7	21	8	40	34	37	3	22	20	19	2	6	18	31	12				
109	0.2	600	39	5	27	9	35	17	16	13	4	11	14	33	38	30	23	25	26	10	15	28	40	24	32	22	29	20	21	36	7	34	37	8	3	2	6	19	18	31	12				
110	0.2	700	39	14	30	5	35	23	16	25	4	9	15	38	36	40	21	34	32	3	27	17	24	33	28	11	37	13	29	26	10	22	20	7	2	8	19	6	18	31	12				
111	0.2	800	39	36	13	14	5	35	30	23	16	27	38	34	24	33	37	25	19	32	17	28	9	11	15	4	22	29	20	40	18	31	21	3	2	26	6	10	7	8	12				
112	0.2	900	39	14	13	27	9	24	32	17	16	35	11	15	33	21	38	40	30	5	23	4	22	20	25	26	28	10	36	7	34	3	29	2	6	8	37	19	18	12	31				
113	0.2	1000	39	24	32	14	35	25	13	27	36	38	9	15	5	33	11	17	40	4	28	30	16	29	22	20	34	26	3	21	37	23	19	2	10	6	18	7	8	12	31				
114	0.2	1100	13	30	27	16	25	24	9	15	39	5	35	14	4	21	11	33	17	23	26	28	22	29	40	32	20	10	36	7	34	37	19	3	2	38	6	8	18	12	31				
115	0.2	1200	13	16	32	5	35	25	9	15	24	39	17	40	38	26	30	11	14	27	33	10	21	36	7	23	28	29	34	22	8	20	37	19	4	18	31	3	2	6	12				
116	0.2	1300	39	14	16	13	30	23	24	35	5	9	15	22	40	17	38	20	21	32	11	27	4	36	28	33	29	34	25	3	26	2	10	37	6	7	8	19	18	31	12				
117	0.2	1400	39	9	15	14	25	30	5	32	16	11	13	40	36	38	34	24	4	27	23	33	35	21	17	3	37	22	28	19	18	20	26	31	10	7	29	8	2	6	12				
118	0.2	1500	13	16	32	24	5	14	4	30	39	23	27	35	28	33	9	29	11	15	17	40	21	22	25	38	26	20	10	36	7	8	34	3	2	37	19	6	18	31	12				
119	0.2	1600	13	36	27	9	17	30	33	34	14	23	28	38	24	16	37	35	29	19	11	15	18	5	21	40	32	31	39	22	25	4	3	26	10	20	7	8	2	6	12				
120	0.2	1700	39	30	9	15	27	25	17	35	13	23	14	16	11	24	26	10	21	36	7	22	38	32	28	20	33	5	34	29	37	19	40	4	3	18	2	8	31	6	12				
121	0.2	1800	39	25	17	16	35	9	15	32	40	30	23	24	38	21	27	22	36	33	14	11	28	29	5	4	34	3	13	26	20	2	37	10	19	18	31	7	8	6	12				
122	0.2	1900	13	38	14	25	5	24	39	17	9	15	4	30	35	40	11	16	32	21	26	10	27	36	7	33	8	34	3	22	20	23	37	19	2	18	28	29	31	6	12				
123	0.2	2000	13	38	14	9	30	39	36	34	27	35	17	16	25	33	11	15	24	40	26	37	23	32	21	5	19	10	28	22	29	4	18	20	7	8	31	3	2	6	12				
124	0.2	2100	13	27	5	33	24	35	9	15	4	32	28	39	14	21	40	38	16	25	11	17	26	22	20	30	10	23	29	36	7	8	34	37	3	19	2	6	18	31	12				
125	0.2	2200	13	24	9	30	17	35	36	25	26	5	11	15	32	40	4	16	38	22	27	20	33	21	14	34	39	28	23	29	37	3	2	6	10	7	19	18	8	12	31				
126	0.2	2300	13	17	30	16	9	15	14	39	36	5	40	24	22	27	34	32	38	4	20	11	37	35	21	3	23	19	25	26	18	10	28	31	7	33	2	29	6	12	8				
127	0.2	2400	13	9	15	38	39	35	40	16	5	32	14	27	24	36	25	17	34	21	30	26	28	33	29	11	4	10	22	23	37	7	20	3	2	19	6	18	31	12	8				
128	0.2	2500	39	38	17	25	30	9	15	32	14	24	35	11	5	16	40	27	33	21	13	26	22	4	10	28	23	36	7	20	29	34	37	19	18	3	31	8	2	6	12				

Table 7-22 Sequence, routings and cost estimates of remanufacturing function (10/44)

Test No.	Remanufacturing Method (1=Reuse, 2=Reincarnate, 3=Recycle, 4=Disposal)																																										Cost (£)
103	3	4	1	2	3	3	1	3	3	3	1	1	3	4	1	1	4	2	4	3	4	1	3	3	3	3	3	2	1	3	3	2	3	1	1	2	2	2	3	2	32,651
104	1	3	3	1	2	4	3	1	3	1	3	1	1	4	3	4	3	3	2	3	2	4	2	3	2	3	1	1	3	1	3	3	4	3	2	3	1	3	2	2	32,667
105	1	1	4	1	3	1	4	3	1	4	2	1	3	2	3	3	3	3	3	4	3	1	3	4	1	3	2	2	3	1	3	3	2	1	3	2	3	3	2	2	32,683
106	3	4	1	3	1	3	1	3	1	4	4	1	3	3	2	3	3	4	2	2	1	1	3	3	3	4	3	3	1	3	1	3	2	1	2	2	3	3	2	2	32,699
107	3	3	4	1	2	3	3	4	1	1	1	1	3	1	3	3	4	3	4	3	3	3	2	1	3	3	1	2	2	4	3	2	2	1	1	3	3	3	2	2	32,715
108	1	3	1	3	1	4	3	3	1	2	4	3	2	4	1	1	3	3	3	1	2	2	3	4	2	3	3	1	3	3	4	3	3	1	2	3	3	1	2	2	32,723
109	1	4	4	1	4	3	1	3	1	2	2	3	3	1	3	3	1	2	3	2	1	3	1	3	3	3	3	4	2	3	3	3	4	2	3	1	3	1	2	2	32,739
110	1	2	1	4	4	3	1	3	1	1	3	3	4	1	3	3	1	4	4	3	3	3	2	2	3	3	3	1	2	3	3	2	2	3	1	3	3	1	2	2	32,763
111	1	4	3	2	4	4	1	3	1	4	3	3	3	3	3	3	1	1	3	2	1	2	3	1	3	3	3	1	3	1	3	4	2	1	3	2	2	3	2	2	32,779
112	1	2	3	4	1	3	1	3	1	4	2	3	3	3	3	1	1	4	3	1	3	3	3	1	2	2	4	2	3	4	3	2	3	3	3	1	3	2	1	2	32,787
113	1	3	1	2	4	3	3	4	4	3	1	3	4	3	2	3	1	1	2	1	1	3	3	3	3	1	4	3	3	3	1	2	2	3	3	2	3	2	1	2	32,810
114	3	1	4	1	3	3	1	3	1	4	4	2	1	3	2	3	3	3	1	2	3	3	1	1	3	2	4	2	3	3	1	4	2	3	3	3	3	2	1	2	32,819
115	3	1	1	4	4	3	1	3	3	1	3	1	3	1	1	2	2	4	3	2	3	4	2	3	2	3	3	3	3	3	3	1	1	3	1	4	2	3	2	2	32,834
116	1	2	1	3	1	3	3	4	4	1	3	3	1	3	3	3	3	1	2	4	1	4	2	3	3	3	3	4	1	2	2	3	3	2	3	1	3	1	2	2	32,858
117	1	1	3	2	3	1	4	1	1	2	3	1	4	3	3	3	1	4	3	3	4	3	3	4	3	3	2	1	3	3	1	1	2	2	3	3	2	3	2	2	32,874
118	3	1	1	3	4	2	1	1	1	3	4	4	2	3	1	3	2	3	3	1	3	3	3	3	1	3	2	4	2	3	3	4	2	3	1	3	3	1	2	2	32,882
119	3	4	4	1	3	1	3	3	2	3	2	3	3	1	3	4	3	1	2	3	3	4	3	1	1	1	1	3	3	1	4	1	2	3	2	3	2	3	2	2	32,906
120	1	1	1	3	4	3	3	4	3	3	2	1	2	3	1	2	3	4	2	3	3	1	2	3	3	4	3	3	3	1	1	1	4	3	2	3	1	3	2	2	32,914
121	1	3	3	1	4	1	3	1	1	1	3	3	3	3	4	3	4	3	2	2	2	3	4	1	3	4	3	1	3	2	3	2	1	3	1	2	3	3	2	2	32,938
122	3	3	2	3	4	3	1	3	1	3	1	1	4	1	2	1	1	3	1	2	4	4	2	3	3	3	4	3	3	3	3	1	2	3	2	3	1	3	2	2	32,946
123	3	3	2	1	1	1	4	3	4	4	3	1	3	3	2	3	3	1	1	3	3	1	3	4	1	2	2	3	3	1	3	3	2	3	1	4	2	3	2	2	32,969
124	3	4	4	3	3	4	1	3	1	1	2	1	2	3	1	3	1	3	2	3	1	3	3	1	2	3	3	4	2	3	3	3	4	1	2	3	3	1	2	2	32,978
125	3	3	1	1	3	4	4	3	1	4	2	3	1	1	1	1	3	3	4	3	3	3	2	3	1	2	3	3	3	4	2	3	2	2	1	3	3	2	1	2	33,001
126	3	3	1	1	1	3	2	1	4	4	1	3	3	4	3	1	3	1	3	2	3	4	3	4	3	1	3	1	3	2	2	1	2	3	2	3	3	2	3	2	33,017
127	3	1	3	3	1	4	1	1	4	1	2	4	3	4	3	3	3	3	1	1	2	3	3	2	1	2	3	3	3	2	3	4	2	1	3	3	1	2	3	2	33,033
128	1	3	3	3	1	1	3	1	2	3	4	2	4	1	1	4	3	3	3	1	3	1	2	2	3	4	2	3	3	3	3	1	3	4	1	3	2	3	2	2	33,041

Table 7-23 Sequence, routings and cost estimates of remanufacturing function (11/44)

Test No.	Quality (q)	Distance (km)	Disassembly sequence (by Part Number)																																											
129	0.2	2600	39	9	38	14	11	15	24	36	16	17	5	30	25	13	26	35	23	10	27	33	34	22	40	37	28	19	29	18	21	7	32	4	20	8	31	3	2	6	12
130	0.2	2700	39	9	16	32	17	11	38	27	24	35	30	36	34	23	25	14	13	28	26	5	37	10	15	7	33	19	8	21	40	18	31	4	3	29	22	20	2	6	12
131	0.2	2800	13	16	17	30	38	27	35	14	32	23	33	25	26	9	15	24	40	11	39	22	20	10	36	7	34	28	8	29	5	4	3	21	37	19	18	31	2	6	12
132	0.2	2900	13	25	14	17	9	30	16	11	15	39	26	10	23	32	36	7	5	27	24	28	35	22	4	34	33	3	20	21	38	40	2	6	8	37	29	19	18	31	12
133	0.2	3000	39	16	17	25	5	13	4	26	27	32	33	9	15	11	38	24	14	35	21	10	36	7	8	30	28	22	29	23	40	20	34	3	2	37	19	18	6	31	12
134	0.2	3100	13	5	25	32	24	39	30	4	27	17	9	15	16	36	38	35	26	33	23	28	11	14	34	37	29	19	18	31	21	22	40	20	3	2	6	10	7	8	12
135	0.2	3200	13	17	39	16	30	25	27	36	23	32	9	15	34	22	35	38	21	33	20	14	28	40	5	11	37	4	24	26	3	2	29	10	6	19	7	8	18	31	12
136	0.2	3300	13	35	30	9	15	17	5	23	21	24	36	25	11	16	26	32	38	34	40	22	27	20	14	4	39	3	37	33	28	2	29	10	7	19	18	8	6	12	31
137	0.2	3400	13	5	38	32	17	30	14	9	15	25	26	27	11	40	10	35	36	7	21	39	24	33	16	34	23	28	37	22	19	29	20	8	4	3	2	6	18	12	31
138	0.2	3500	13	24	16	9	17	25	35	26	5	4	32	14	30	39	11	15	10	36	7	23	8	34	21	27	3	37	40	33	28	38	29	19	18	22	20	31	2	6	12
139	0.2	3600	13	5	38	35	9	39	14	4	32	30	23	11	15	16	21	40	36	17	25	27	26	34	3	28	33	10	24	7	8	29	37	19	22	18	31	20	2	6	12
140	0.2	3700	13	27	5	16	17	28	33	36	25	14	30	32	34	35	38	23	39	9	11	29	26	4	3	24	37	10	15	19	7	18	22	8	20	21	31	2	6	12	40
141	0.2	3800	13	5	9	16	17	14	30	39	11	15	38	32	25	40	26	10	36	7	35	22	8	21	23	24	27	20	33	28	34	4	29	37	19	3	2	6	18	31	12
142	0.2	3900	39	36	24	9	15	13	35	40	30	27	14	25	38	34	5	23	17	16	4	28	22	3	11	32	26	37	10	33	7	8	19	20	21	29	2	6	18	31	12
143	0.2	4000	39	9	32	24	11	15	17	40	16	14	30	38	35	22	21	5	13	20	25	26	27	10	28	33	29	23	4	36	7	34	8	37	19	3	2	6	18	31	12
144	0.2	4100	39	35	14	5	36	32	38	34	4	3	13	9	24	25	11	15	16	22	37	40	27	28	33	17	21	26	30	29	20	10	23	2	7	8	19	18	6	12	31
145	0.2	4200	39	30	23	32	14	13	27	24	38	9	15	16	22	17	25	11	35	21	20	5	4	40	26	10	36	7	28	34	33	37	8	3	2	29	19	6	18	31	12
146	0.2	4300	13	25	36	5	4	9	15	11	30	16	24	39	27	33	34	28	3	32	14	17	35	21	38	37	23	29	22	19	18	26	20	2	10	31	6	12	40	7	8
147	0.2	4400	13	30	17	38	14	27	16	5	39	28	9	15	23	32	33	22	29	24	40	4	25	20	11	35	26	10	36	7	34	3	37	8	21	2	19	6	18	31	12
148	0.2	4500	13	9	15	11	16	35	38	40	30	39	27	32	21	24	17	5	25	4	26	33	14	10	28	36	7	8	29	23	22	20	34	3	2	37	6	19	18	12	31
149	0.2	4600	13	14	38	17	5	9	32	4	16	25	24	39	11	15	35	36	30	21	34	3	40	22	23	20	37	19	27	28	18	31	26	10	33	29	2	7	6	12	8
150	0.2	4700	39	38	17	32	14	35	5	13	16	9	15	25	21	11	26	24	40	27	10	33	36	7	8	4	22	34	28	30	3	23	37	29	19	20	2	6	18	31	12
151	0.2	4800	13	5	36	14	30	9	15	16	38	24	17	35	25	4	40	21	27	34	22	26	32	23	11	10	28	33	20	39	37	19	3	29	2	18	6	31	7	8	12
152	0.2	4900	39	9	16	14	38	11	15	32	24	25	13	30	5	4	40	23	35	21	17	22	20	27	28	26	10	36	7	33	29	34	3	8	37	2	6	19	18	12	31
153	0.2	5000	39	30	24	36	5	16	9	15	14	13	27	33	38	11	4	23	34	32	17	28	37	19	35	29	22	3	21	18	31	20	40	2	25	26	10	7	8	6	12

Table 7-24 Sequence, routings and cost estimates of remanufacturing function (12/44)

Test No.	Remanufacturing Method (1=Reuse, 2=Reincarnate, 3=Recycle, 4=Disposal)																																											Cost (£)
129	1	1	3	2	2	3	3	4	1	3	4	1	3	3	1	4	3	2	4	3	3	3	1	3	2	1	3	3	3	2	1	1	3	3	1	4	2	3	2	2	33,065
130	1	1	1	1	3	2	3	4	3	4	1	4	3	3	3	2	3	2	1	4	3	2	3	2	3	1	3	3	1	3	1	1	4	3	3	3	2	3	2	2	33,081
131	3	1	3	1	3	4	4	2	1	3	3	3	1	1	3	3	1	2	1	3	3	2	4	2	3	2	3	3	4	1	4	3	3	1	3	1	2	3	2	2	33,089
132	3	3	2	3	1	1	1	2	3	1	1	2	3	1	4	2	4	4	3	2	4	3	1	3	3	4	3	3	3	1	2	3	3	3	3	1	3	1	2	2	33,105
133	1	1	3	3	4	3	1	1	4	1	3	1	3	2	3	3	2	4	3	2	4	2	3	1	2	3	3	3	1	3	3	4	2	3	1	3	3	1	2	2	33,121
134	3	4	3	1	3	1	1	1	4	3	1	3	1	4	3	4	1	3	3	2	2	2	3	3	3	1	3	1	3	3	1	3	4	2	3	2	2	3	2	2	33,144
135	3	3	1	1	1	3	4	4	3	1	1	3	3	3	4	3	3	3	3	2	2	1	4	2	3	1	3	1	4	2	3	2	3	1	2	3	3	1	2	2	33,160
136	3	4	1	1	3	3	4	3	3	3	4	3	2	1	1	1	3	3	1	3	4	3	2	1	1	4	3	3	2	2	3	2	2	1	3	3	3	2	1	2	33,176
137	3	4	3	1	3	1	2	1	3	3	1	4	2	1	2	4	4	2	3	1	3	3	1	3	3	2	3	3	1	3	3	3	1	4	2	3	3	2	1	2	33,184
138	3	3	1	1	3	3	4	1	4	1	1	2	1	1	2	3	2	4	2	3	3	3	3	4	4	3	1	3	2	3	3	1	3	3	3	1	2	3	2	2	33,200
139	3	4	3	4	1	1	2	1	1	1	3	2	3	1	3	1	4	3	3	4	1	3	4	2	3	2	3	2	3	3	3	1	3	3	1	3	2	3	2	2	33,224
140	3	4	4	1	3	2	3	4	3	2	1	1	3	4	3	3	1	1	2	3	1	1	4	3	3	2	3	1	2	3	3	3	3	3	1	2	3	2	1	2	33,240
141	3	4	1	1	3	2	1	1	2	3	3	1	3	1	1	2	4	2	4	3	3	3	3	3	4	3	3	2	3	1	3	3	1	4	2	3	3	1	2	2	33,248
142	1	4	3	1	3	3	4	1	1	4	2	3	3	3	4	3	3	1	1	2	3	4	2	1	1	3	2	3	2	3	1	3	3	3	2	3	3	1	2	2	33,272
143	1	1	1	3	2	3	3	1	1	2	1	3	4	3	3	4	3	3	3	1	4	2	2	3	3	3	1	4	2	3	3	3	1	4	2	3	3	1	2	2	33,280
144	1	4	2	4	4	1	3	3	1	4	3	1	3	3	2	3	1	3	3	1	4	2	3	3	3	1	1	3	3	2	3	2	2	3	1	3	3	2	1	2	33,303
145	1	1	3	1	2	3	4	3	3	1	3	1	3	3	3	2	4	3	3	4	1	1	1	2	4	2	2	3	3	3	3	4	2	3	1	3	3	1	2	2	33,311
146	3	3	4	4	1	1	3	2	1	1	3	1	4	3	3	2	4	1	2	3	4	3	3	3	3	3	3	1	3	1	3	2	2	1	3	2	1	2	3	2	33,335
147	3	1	3	3	2	4	1	4	1	2	1	3	3	1	3	3	3	3	1	1	3	3	2	4	1	2	4	2	3	4	3	3	3	2	1	3	3	1	2	2	33,343
148	3	1	3	2	1	4	3	1	1	1	4	1	3	3	3	4	3	1	1	3	2	2	2	4	2	3	3	3	3	3	3	4	2	3	3	1	3	2	1	2	33,359
149	3	2	3	3	4	1	1	1	1	3	3	1	2	3	4	4	1	3	3	4	1	3	3	3	3	1	4	2	3	1	1	2	3	3	2	2	3	2	3	2	33,383
150	1	3	3	1	2	4	4	3	1	1	3	3	3	2	1	3	1	4	2	3	4	2	3	1	3	3	2	1	4	3	3	3	1	3	2	3	3	1	2	2	33,391
151	3	4	4	2	1	1	3	1	3	3	3	4	3	1	1	3	4	3	3	1	1	3	2	2	2	3	3	1	3	1	4	3	2	3	3	1	2	3	2	2	33,415
152	1	1	1	2	3	2	3	1	3	3	3	1	4	1	1	3	4	3	3	3	3	4	2	1	2	4	2	3	3	3	4	3	3	2	3	1	3	2	1	2	33,423
153	1	1	3	4	4	1	1	3	2	3	4	3	3	2	1	3	3	1	3	2	3	1	4	3	3	4	3	3	1	3	1	2	3	1	2	2	3	3	2	2	33,446

Table 7-25 Sequence, routings and cost estimates of remanufacturing function (13/44)

Test No.	Quality (q)	Distance (km)	Disassembly sequence (by Part Number)																																										
154	0.3	0	39	14	9	32	30	11	38	16	17	13	5	25	24	26	35	27	23	28	10	15	36	7	4	34	21	40	3	22	20	33	2	37	19	18	29	6	12	8	31
155	0.3	100	39	14	24	13	27	9	5	30	17	25	26	35	16	11	32	28	23	4	10	15	33	40	22	29	36	7	38	34	20	21	3	37	2	6	19	18	31	12	8
156	0.3	200	13	36	30	27	34	9	14	33	24	39	37	17	11	5	28	25	23	19	38	18	4	3	32	35	31	26	10	15	16	21	29	7	22	40	8	20	2	6	12
157	0.3	300	13	5	38	27	35	30	16	17	14	25	4	39	28	9	24	11	15	33	22	40	32	26	21	10	23	36	7	34	20	3	29	2	8	6	37	19	18	31	12
158	0.3	400	39	27	9	15	16	17	36	14	35	30	5	21	22	23	13	20	4	11	33	34	38	25	24	37	28	19	18	26	3	29	10	2	7	32	8	40	6	31	12
159	0.3	500	13	16	30	5	36	9	25	17	27	4	35	34	24	3	38	14	11	15	22	32	21	33	37	28	26	10	23	29	40	20	2	19	7	18	8	31	39	6	12
160	0.3	600	39	35	38	30	27	25	28	17	36	14	23	5	4	13	9	15	26	21	33	11	32	29	10	24	16	22	40	34	37	7	19	3	20	8	2	18	31	6	12
161	0.3	700	13	9	11	15	16	5	39	30	35	40	25	27	21	33	32	22	38	17	23	20	28	4	29	14	24	26	10	36	7	8	34	37	19	3	2	18	31	6	12
162	0.3	800	13	39	9	25	38	27	35	28	32	33	24	14	30	11	16	5	29	4	23	17	26	36	10	15	34	37	22	3	7	19	18	20	21	40	31	8	2	6	12
163	0.3	900	39	24	25	16	17	38	14	13	26	9	32	11	10	15	27	28	36	7	8	33	5	30	34	37	35	4	22	29	21	20	3	23	2	40	6	19	18	12	31
164	0.3	1000	39	9	24	5	14	4	27	13	17	28	38	25	11	26	33	35	10	15	30	36	7	16	22	32	23	34	37	40	29	20	19	21	3	2	18	6	31	8	12
165	0.3	1100	13	35	32	27	14	28	25	24	17	9	15	39	26	40	38	11	33	10	30	23	29	21	16	22	36	7	5	20	4	34	37	3	19	2	6	18	12	8	31
166	0.3	1200	13	14	9	38	36	11	15	24	32	39	40	16	30	27	25	33	22	5	4	28	34	3	29	17	23	20	37	19	35	18	26	10	21	31	7	2	6	12	8
167	0.3	1300	39	17	13	5	24	27	9	32	16	33	25	28	4	38	14	26	30	11	15	10	23	22	35	36	7	8	21	40	20	29	34	37	3	19	18	31	2	6	12
168	0.3	1400	13	30	9	32	5	38	27	17	25	28	24	26	16	4	11	15	23	40	33	35	29	14	22	39	10	36	7	20	34	21	37	19	3	8	18	2	31	6	12
169	0.3	1500	39	13	25	9	35	11	15	27	5	21	36	32	24	30	4	40	38	14	34	16	17	22	37	23	3	28	26	19	20	10	7	8	18	33	31	29	2	6	12
170	0.3	1600	13	24	9	25	27	33	38	11	15	36	28	40	14	16	35	5	34	4	22	37	39	3	17	32	30	20	26	29	23	10	7	19	8	21	2	18	6	12	31
171	0.3	1700	39	32	36	14	38	35	27	9	15	25	17	5	30	28	13	24	4	11	33	26	10	16	40	21	34	37	3	29	23	22	20	19	7	2	6	8	18	12	31
172	0.3	1800	39	9	15	13	35	30	14	32	23	40	17	5	25	4	27	28	38	11	26	16	22	10	33	20	29	24	36	7	8	34	37	19	18	3	21	2	31	6	12
173	0.3	1900	13	17	38	5	35	14	32	9	15	25	16	22	30	39	40	26	20	21	24	11	4	23	27	28	10	36	7	33	34	3	2	6	8	29	37	19	18	31	12
174	0.3	2000	39	32	16	13	5	35	24	17	9	14	36	34	27	25	33	4	26	11	15	22	40	3	21	38	37	10	20	7	2	8	30	23	19	18	28	6	31	12	29
175	0.3	2100	39	9	15	14	38	40	5	13	11	24	30	4	23	25	17	32	26	10	16	36	7	34	3	22	35	20	27	28	8	21	33	29	2	6	37	19	18	31	12
176	0.3	2200	39	5	25	35	14	24	30	23	13	17	9	27	38	16	33	28	32	11	26	29	10	15	4	21	22	36	7	40	34	8	37	19	20	3	18	31	2	6	12
177	0.3	2300	13	24	35	16	36	39	25	30	23	17	9	15	14	40	21	5	32	38	11	22	26	34	27	10	28	33	20	7	4	8	29	37	3	2	19	6	18	31	12
178	0.3	2400	13	36	27	39	30	9	15	5	4	14	35	11	33	32	23	38	34	37	28	29	16	24	19	17	25	3	40	22	18	20	26	21	10	31	2	6	12	7	8
179	0.3	2500	39	25	35	13	16	17	5	4	24	9	38	27	32	33	26	28	14	11	15	30	21	10	23	29	22	36	7	20	40	8	34	3	2	6	37	19	18	31	12

Table 7-26 Sequence, routings and cost estimates of remanufacturing function (14/44)

Test No.	Remanufacturing Method (1=Reuse, 2=Reincarnate, 3=Recycle, 4=Disposal)																																											Cost (£)
154	1	2	1	1	1	2	3	1	3	3	4	3	3	1	4	4	3	2	2	3	4	2	1	3	3	1	4	3	3	3	2	3	1	3	3	3	2	3	1	2	31,553
155	1	2	3	3	4	1	4	1	3	3	1	4	1	2	1	2	3	1	2	3	3	1	3	3	4	2	3	3	3	3	4	3	2	3	1	3	1	2	3	2	31,569
156	3	4	1	4	3	1	2	3	3	1	3	3	2	4	2	3	3	1	3	3	1	4	1	4	1	1	2	3	1	3	3	2	3	1	3	3	2	3	2	2	31,592
157	3	4	3	4	4	1	1	3	2	3	1	1	2	1	3	2	3	3	3	1	1	1	3	2	3	4	2	3	3	4	3	2	3	3	3	1	3	1	2	2	31,601
158	1	4	1	3	1	3	4	2	4	1	4	3	3	3	3	3	1	2	3	3	3	3	3	3	2	1	3	1	4	3	2	2	2	1	3	1	3	1	2	2	31,624
159	3	1	1	4	4	1	3	3	4	1	4	3	3	4	3	2	2	3	3	1	3	3	3	2	1	2	3	3	1	3	2	1	2	3	3	1	1	3	2	2	31,640
160	1	4	3	1	4	3	2	3	4	2	3	4	1	3	1	3	1	3	3	2	1	3	2	3	1	3	1	3	3	2	1	4	3	3	2	3	1	3	2	2	31,656
161	3	1	2	3	1	4	1	1	4	1	3	4	3	3	1	3	3	3	3	3	2	1	3	2	3	1	2	4	2	3	3	3	1	4	2	3	1	3	2	2	31,665
162	3	1	1	3	3	4	4	2	1	3	3	2	1	2	1	4	3	1	3	3	1	4	2	3	3	3	3	4	2	1	3	3	3	1	1	3	2	3	2	2	31,688
163	1	3	3	1	3	3	2	3	1	1	1	2	2	3	4	2	4	2	3	3	4	1	3	3	4	1	3	3	3	3	4	3	2	1	3	1	3	2	1	2	31,696
164	1	1	3	4	2	1	4	3	3	2	3	3	2	1	3	4	2	3	1	4	2	1	3	1	3	3	3	1	3	3	1	3	4	2	3	3	1	3	2	2	31,712
165	3	4	1	4	2	2	3	3	3	1	3	1	1	1	3	2	3	2	1	3	3	3	1	3	4	2	4	3	1	3	3	4	1	2	3	3	2	3	1	2	31,728
166	3	2	1	3	4	2	3	3	1	1	1	1	1	4	3	3	3	4	1	2	3	4	3	3	3	3	3	1	4	3	1	2	3	1	2	2	3	2	3	2	31,751
167	1	3	3	4	3	4	1	1	1	3	3	2	1	3	2	1	1	2	3	2	3	3	4	4	2	3	3	1	3	3	3	3	4	1	3	1	2	3	2	2	31,760
168	3	1	1	1	4	3	4	3	3	2	3	1	1	1	2	3	3	1	3	4	3	2	3	1	2	4	2	3	3	3	3	1	4	3	3	2	1	3	2	2	31,776
169	1	3	3	1	4	2	3	4	4	3	4	1	3	1	1	1	3	2	3	1	3	3	3	3	4	2	1	1	3	2	2	3	3	3	1	3	2	3	2	2	31,799
170	3	3	1	3	4	3	3	2	3	4	2	1	2	1	4	4	3	1	3	3	1	4	3	1	1	3	1	3	3	2	2	1	3	3	2	3	3	2	1	2	31,815
171	1	1	4	2	3	4	4	1	3	3	3	4	1	2	3	3	1	2	3	1	2	1	1	3	3	3	4	3	3	3	3	1	2	2	3	3	3	2	1	2	31,831
172	1	1	3	3	4	1	2	1	3	1	3	4	3	1	4	2	3	2	1	1	3	2	3	3	3	3	4	2	3	3	3	1	3	4	3	2	1	3	2	2	31,839
173	3	3	3	4	4	2	1	1	3	3	1	3	1	1	1	1	3	3	3	2	1	3	4	2	2	4	2	3	3	4	2	3	3	3	3	1	3	1	2	2	31,855
174	1	1	1	3	4	4	3	3	1	2	4	3	4	3	3	1	1	2	3	3	1	4	3	3	3	2	3	2	2	3	1	3	1	3	2	3	1	2	3	2	31,879
175	1	1	3	2	3	1	4	3	2	3	1	1	3	3	3	1	1	2	1	4	2	3	4	3	4	3	4	2	3	3	3	3	2	3	3	1	3	1	2	2	31,887
176	1	4	3	4	2	3	1	3	3	3	1	4	3	1	3	2	1	2	1	3	2	3	1	3	3	4	2	1	3	3	3	1	3	4	3	1	2	3	2	2	31,903
177	3	3	4	1	4	1	3	1	3	3	1	3	2	1	3	4	1	3	2	3	1	3	4	2	2	3	3	2	1	3	3	3	4	2	1	3	3	1	2	2	31,926
178	3	4	4	1	1	1	3	4	1	2	4	2	3	1	3	3	3	3	2	3	1	3	1	3	3	4	1	3	3	3	1	3	2	1	2	3	2	2	3	2	31,942
179	1	3	4	3	1	3	4	1	3	1	3	4	1	3	1	2	2	2	3	1	3	2	3	3	3	4	2	3	1	3	3	4	2	3	3	1	3	1	2	2	31,951

Table 7-27 Sequence, routings and cost estimates of remanufacturing function (15/44)

Test No.	Quality (q)	Distance (km)	Disassembly sequence (by Part Number)																																											
180	0.3	2600	39	16	35	24	9	15	32	30	11	17	22	5	20	38	4	14	25	23	13	26	40	21	27	28	33	10	36	7	8	29	34	3	2	6	37	19	18	31	12
181	0.3	2700	39	14	32	35	24	30	38	9	15	27	11	21	13	25	40	5	28	17	4	33	26	10	16	23	22	20	36	7	29	34	37	8	19	18	3	31	2	6	12
182	0.3	2800	13	32	30	25	24	38	14	35	5	39	36	4	9	15	34	11	40	21	16	37	23	3	22	19	17	26	18	10	7	31	20	27	33	2	8	6	12	28	29
183	0.3	2900	13	36	30	17	9	11	15	14	24	27	23	32	35	5	38	39	25	21	28	34	33	16	40	26	29	10	22	7	20	4	8	3	37	19	18	31	2	6	12
184	0.3	3000	39	24	13	17	16	30	9	27	33	5	32	38	35	36	23	28	29	4	25	14	26	34	11	3	10	15	37	19	40	7	21	22	18	31	8	20	2	6	12
185	0.3	3100	39	24	14	25	27	17	13	32	16	36	28	33	5	30	38	23	9	15	29	4	40	26	11	35	34	22	20	21	37	10	3	7	2	8	19	6	18	12	31
186	0.3	3200	13	9	15	36	17	35	34	5	32	39	40	27	16	30	11	4	38	25	26	3	14	21	28	37	23	22	33	24	29	19	10	7	18	8	20	31	2	6	12
187	0.3	3300	39	16	9	11	15	5	24	30	35	32	38	13	4	25	23	14	27	28	36	33	34	21	37	17	3	22	29	19	40	26	20	18	10	31	2	7	6	8	12
188	0.3	3400	39	38	9	11	15	27	24	33	32	40	30	17	14	23	25	36	35	5	21	16	22	34	28	37	13	19	26	18	10	31	29	4	3	20	2	7	8	6	12
189	0.3	3500	13	30	38	9	39	14	35	36	17	25	11	15	5	16	22	21	23	20	4	34	32	24	26	27	28	40	37	3	10	33	29	7	8	19	18	31	2	6	12
190	0.3	3600	39	9	15	38	16	24	32	22	27	25	36	28	14	34	35	30	40	23	21	17	11	33	29	13	26	20	5	4	10	3	2	6	7	8	37	19	18	12	31
191	0.3	3700	13	5	35	9	11	15	14	32	25	16	21	36	27	39	24	28	17	22	38	20	30	26	10	7	34	40	37	4	3	33	23	19	18	2	8	29	31	6	12
192	0.3	3800	39	32	36	9	15	25	30	27	5	11	34	24	13	4	14	37	17	35	3	16	38	28	33	21	22	26	10	40	20	7	29	8	2	23	19	18	31	6	12
193	0.3	3900	13	9	5	11	15	27	38	30	35	23	28	16	24	4	14	36	32	17	34	40	21	25	26	10	7	39	37	8	3	22	33	29	20	2	6	19	18	31	12
194	0.3	4000	39	32	25	13	36	30	5	17	27	33	26	4	24	34	3	16	9	15	37	14	28	22	35	38	11	21	29	10	20	2	6	40	7	8	23	19	18	31	12
195	0.3	4100	39	14	24	27	5	38	35	28	9	15	32	36	25	30	13	23	33	4	11	34	16	29	37	22	40	19	18	17	26	10	7	20	21	31	8	3	2	6	12
196	0.3	4200	13	14	16	25	9	5	38	39	30	23	11	15	22	4	17	27	20	28	24	26	35	10	36	7	21	33	40	29	34	37	3	19	32	8	18	31	2	6	12
197	0.3	4300	39	16	9	15	35	14	27	17	22	38	25	5	30	32	28	13	23	21	40	24	36	4	33	26	11	20	29	10	34	3	7	2	8	37	19	18	31	6	12
198	0.3	4400	13	36	38	17	16	9	15	27	40	34	30	39	22	20	11	35	5	14	4	28	21	33	32	29	23	25	37	26	10	24	7	19	8	3	2	6	18	12	31
199	0.3	4500	39	9	16	11	15	5	24	40	30	38	13	14	22	23	25	17	36	27	32	33	20	34	35	21	28	26	4	29	3	10	37	7	2	6	8	19	18	31	12
200	0.3	4600	39	13	27	30	16	28	33	23	25	9	15	35	14	29	21	22	24	17	38	36	32	34	20	37	40	19	11	18	5	26	4	10	31	7	3	8	2	6	12
201	0.3	4700	39	30	27	16	9	15	24	11	22	25	23	32	35	17	28	14	38	13	20	26	10	5	21	40	4	36	7	33	34	29	3	2	8	37	6	19	18	12	31
202	0.3	4800	13	24	9	15	17	32	35	5	30	25	14	27	21	16	23	33	11	38	40	28	26	29	10	22	20	4	39	36	7	8	34	37	3	19	18	2	31	6	12
203	0.3	4900	13	32	27	5	14	39	25	24	30	9	28	17	11	15	38	4	35	23	40	21	33	16	26	10	29	36	7	8	34	3	37	19	18	31	22	20	2	6	12
204	0.3	5000	13	5	35	14	39	17	4	30	24	36	34	32	37	38	9	15	11	25	27	28	21	33	23	26	29	10	7	40	19	8	3	16	18	22	31	20	2	6	12

Table 7-28 Sequence, routings and cost estimates of remanufacturing function (16/44)

Test No.	Remanufacturing Method (1=Reuse, 2=Reincarnate, 3=Recycle, 4=Disposal)																																										Cost (£)
180	1	1	4	3	1	3	1	1	2	3	3	4	3	3	1	2	3	3	3	1	1	3	4	2	3	2	4	2	3	3	3	4	2	3	3	1	3	1	2	2	31,967
181	1	2	1	4	3	1	3	1	3	4	2	3	3	3	1	4	2	3	1	3	1	2	1	3	3	3	4	2	3	3	3	3	1	3	4	1	2	3	2	2	31,983
182	3	1	1	3	3	3	2	4	4	1	4	1	1	3	3	2	1	3	1	3	3	4	3	1	3	1	3	2	2	1	3	4	3	2	3	3	2	2	3	2	32,006
183	3	4	1	3	1	2	3	2	3	4	3	1	4	4	3	1	3	3	2	3	3	1	1	1	3	2	3	2	3	1	3	4	3	1	3	1	2	3	2	2	32,022
184	1	3	3	3	1	1	1	4	3	4	1	3	4	4	3	2	3	1	3	2	1	3	2	4	2	3	3	1	1	2	3	3	3	1	3	3	2	3	2	2	32,038
185	1	3	2	3	4	3	3	1	1	4	2	3	4	1	3	3	1	3	3	1	1	1	2	4	3	3	3	3	3	2	4	2	2	3	1	3	3	2	1	2	32,054
186	3	1	3	4	3	4	3	4	1	1	1	4	1	1	2	1	3	3	1	4	2	3	2	3	3	3	3	3	3	1	2	2	3	3	3	1	2	3	2	2	32,069
187	1	1	1	2	3	4	3	1	4	1	3	3	1	3	3	2	4	2	4	3	3	3	3	3	4	3	3	1	1	1	3	3	2	1	2	2	3	3	2	2	32,085
188	1	3	1	2	3	4	3	3	1	1	1	3	2	3	3	4	4	4	3	1	3	3	2	3	3	1	1	3	2	1	3	1	4	3	2	2	3	3	2	2	32,101
189	3	1	3	1	1	2	4	4	3	3	2	3	4	1	3	3	3	3	1	3	1	3	1	4	2	1	3	4	2	3	3	2	3	1	3	1	2	3	2	2	32,117
190	1	1	3	3	1	3	1	3	4	3	4	2	2	3	4	1	1	3	3	3	2	3	3	3	1	3	4	1	2	4	2	3	2	3	3	1	3	2	1	2	32,133
191	3	4	4	1	2	3	2	1	3	1	3	4	4	1	3	2	3	3	3	3	1	1	2	2	3	1	3	1	4	3	3	1	3	2	3	3	1	3	2	2	32,149
192	1	1	4	1	3	3	1	4	4	2	3	3	3	1	2	3	3	4	4	1	3	2	3	3	3	1	2	1	3	2	3	3	2	3	1	3	1	3	2	2	32,165
193	3	1	4	2	3	4	3	1	4	3	2	1	3	1	2	4	1	3	3	1	3	3	1	2	2	1	3	3	4	3	3	3	3	2	3	1	3	1	2	2	32,181
194	1	1	3	3	4	1	4	3	4	3	1	1	3	3	4	1	1	3	3	2	2	3	4	3	2	3	3	2	3	2	3	1	2	3	3	1	3	1	2	2	32,197
195	1	2	3	4	4	3	4	2	1	3	1	4	3	1	3	3	3	1	2	3	1	3	3	3	1	1	3	3	1	2	2	3	3	1	3	4	2	3	2	2	32,213
196	3	2	1	3	1	4	3	1	1	3	2	3	3	1	3	4	3	2	3	1	4	2	4	2	3	3	1	3	3	3	4	1	1	3	3	1	2	3	2	2	32,221
197	1	1	1	3	4	2	4	3	3	3	3	4	1	1	2	3	3	3	1	3	4	1	3	1	2	3	3	2	3	4	2	2	3	3	1	3	1	3	2	2	32,244
198	3	4	3	3	1	1	3	4	1	3	1	1	3	3	2	4	4	2	1	2	3	3	1	3	3	3	3	1	2	3	2	1	3	4	2	3	3	2	1	2	32,260
199	1	1	1	2	3	4	3	1	1	3	3	2	3	3	3	3	4	4	1	3	3	3	4	3	2	1	1	3	4	2	3	2	2	3	3	1	3	1	2	2	32,276
200	1	3	4	1	1	2	3	3	3	1	3	4	2	3	3	3	3	3	3	4	1	3	3	3	1	1	2	3	4	1	1	2	1	2	4	3	2	3	2	2	32,292
201	1	1	4	1	1	3	3	2	3	3	3	1	4	3	2	2	3	3	3	1	2	4	3	1	1	4	2	3	3	3	4	2	3	3	3	1	3	2	1	2	32,301
202	3	3	1	3	3	1	4	4	1	3	2	4	3	1	3	3	2	3	1	2	1	3	2	3	3	1	1	4	2	3	3	3	4	1	3	2	1	3	2	2	32,316
203	3	1	4	4	2	1	3	3	1	1	2	3	2	3	3	1	4	3	1	3	3	1	1	2	3	4	2	3	3	4	3	1	3	1	3	3	2	3	2	2	32,332
204	3	4	4	2	1	3	1	1	3	4	3	1	3	3	1	3	2	3	4	2	3	3	3	1	3	2	2	1	1	3	4	1	3	3	1	3	2	3	2	2	32,356

Table 7-29 Sequence, routings and cost estimates of remanufacturing function (17/44)

Test No.	Quality (q)	Distance (km)	Disassembly sequence (by Part Number)																																									
205	0.4	0	39	38	17	16	14	32	5	27	9	15	35	4	33	30	11	13	24	25	40	28	23	29	26	21	10	22	36	7	20	34	3	37	8	19	2	6	18	12	31
206	0.4	100	13	9	15	27	14	35	16	30	22	17	38	40	24	21	33	11	39	20	25	26	5	4	28	32	10	36	7	23	34	8	37	19	29	18	31	3	2	6	12
207	0.4	200	39	5	24	25	4	38	9	36	13	35	30	34	27	37	14	11	15	33	40	32	23	21	19	3	16	17	18	28	29	26	22	20	10	31	2	6	7	8	12
208	0.4	300	13	38	9	15	30	39	24	11	36	5	14	25	16	23	4	27	34	35	33	37	21	22	19	40	28	32	17	29	3	18	31	20	2	6	26	12	10	7	8
209	0.4	400	13	9	27	24	30	25	32	14	28	11	15	35	17	39	33	16	5	40	29	4	22	23	36	21	20	26	34	38	10	3	37	2	6	19	18	31	12	7	8
210	0.4	500	39	25	36	13	9	34	17	26	38	37	11	15	5	24	40	14	27	33	16	35	32	22	21	4	30	28	10	3	7	23	20	29	2	8	6	19	18	31	12
211	0.4	600	39	14	30	38	23	16	24	32	27	9	28	11	15	22	5	33	40	25	36	29	35	13	17	34	21	26	37	10	20	4	19	7	8	18	3	31	2	6	12
212	0.4	700	39	27	25	13	5	36	16	24	35	9	15	4	34	33	14	32	17	28	26	38	21	22	30	3	29	20	2	11	40	6	10	37	23	19	18	12	31	7	8
213	0.4	800	39	14	17	9	35	25	27	11	15	33	40	30	16	22	21	23	32	20	36	34	13	38	37	5	4	3	26	24	2	19	18	6	12	28	10	29	7	31	8
214	0.4	900	39	13	36	32	24	34	27	9	15	28	5	33	37	40	35	38	16	22	11	14	17	25	26	4	10	3	7	8	20	21	30	2	6	23	29	19	18	31	12
215	0.4	1000	39	9	32	14	11	15	13	38	27	35	33	40	25	21	16	30	17	23	26	22	24	20	5	10	36	7	8	28	4	29	34	3	2	6	37	19	18	12	31
216	0.4	1100	39	5	27	35	4	9	15	33	40	28	25	38	16	14	24	11	17	21	22	32	20	30	13	26	23	29	10	36	7	34	8	37	3	2	6	19	18	31	12
217	0.4	1200	39	35	14	17	38	13	16	32	5	27	30	9	23	36	25	28	34	33	37	11	15	4	26	21	29	3	10	22	20	40	24	7	19	18	31	8	2	6	12
218	0.4	1300	13	9	32	17	11	15	30	38	24	23	5	14	39	4	25	26	40	35	16	21	22	20	27	28	10	33	36	7	29	8	34	3	2	6	37	19	18	31	12
219	0.4	1400	39	9	5	27	17	16	32	33	38	28	4	35	14	36	30	29	11	15	25	40	21	22	23	13	20	34	3	2	37	24	6	26	10	19	18	7	8	12	31
220	0.4	1500	39	30	35	32	9	15	27	11	17	28	14	33	21	38	24	16	25	22	40	29	36	20	13	26	34	10	23	37	5	19	4	7	3	18	2	6	31	12	8
221	0.4	1600	39	9	38	24	11	30	17	5	14	36	23	13	35	25	32	27	4	34	26	37	3	10	15	16	28	21	40	7	22	33	20	29	2	6	19	18	31	8	12
222	0.4	1700	13	5	16	17	35	9	15	30	11	40	24	21	27	33	32	23	25	14	28	4	22	20	36	39	29	34	38	26	37	3	10	7	2	8	6	19	18	31	12
223	0.4	1800	13	9	15	35	14	27	40	30	25	16	21	24	32	5	38	17	22	23	11	33	4	26	10	36	7	20	8	39	28	29	34	3	37	19	18	31	2	6	12
224	0.4	1900	13	24	17	9	5	35	14	16	25	26	39	30	38	32	11	15	10	27	33	36	7	34	22	28	8	4	29	37	23	20	3	19	21	18	40	2	6	12	31
225	0.4	2000	39	32	9	15	35	21	30	23	11	14	38	16	25	13	22	27	24	28	33	29	40	36	34	37	5	4	3	19	18	17	31	26	20	10	2	6	7	8	12
226	0.4	2100	13	9	15	16	30	38	27	25	17	24	40	11	33	32	26	5	14	28	10	29	4	39	22	35	36	7	20	8	23	21	34	3	37	2	19	18	31	6	12
227	0.4	2200	13	30	32	5	14	17	24	23	16	36	34	35	39	37	25	38	4	9	15	22	11	20	21	27	40	26	28	33	10	7	3	19	8	18	29	31	2	6	12
228	0.4	2300	39	36	13	24	32	34	16	25	9	15	35	11	27	5	33	30	37	17	28	26	4	23	40	29	38	22	20	14	19	18	31	21	10	3	2	7	8	6	12
229	0.4	2400	39	30	9	16	5	24	11	15	4	27	38	40	33	35	28	25	17	22	32	23	13	14	29	26	20	21	10	36	7	34	37	19	3	2	8	6	18	31	12
230	0.4	2500	39	32	27	38	30	25	5	4	28	17	35	24	16	9	14	11	15	33	13	40	26	10	23	22	29	36	7	34	20	8	3	37	19	18	31	21	2	6	12

Table 7-30 Sequence, routings and cost estimates of remanufacturing function (18/44)

Test No.	Remanufacturing Method (1=Reuse, 2=Reincarnate, 3=Recycle, 4=Disposal)																																										Cost (£)
205	1	3	3	1	2	1	4	4	1	3	4	1	3	1	2	3	3	3	1	2	3	3	1	3	2	3	4	2	3	3	4	3	3	1	2	3	3	2	1	2	30,463
206	3	1	3	4	2	4	1	1	3	3	3	1	3	3	3	2	1	3	3	1	4	1	2	1	2	4	2	3	3	3	3	1	3	3	1	4	2	3	2	2	30,479
207	1	4	3	3	1	3	1	4	3	4	1	3	4	3	2	2	3	3	1	1	3	3	1	4	1	3	3	2	3	1	3	3	2	1	2	3	2	3	2	2	30,502
208	3	3	1	3	1	1	3	2	4	4	2	3	1	3	1	4	3	4	3	3	3	3	1	1	2	1	3	3	4	3	1	3	2	3	1	2	2	2	3	2	30,518
209	3	1	4	3	1	3	1	2	2	2	3	4	3	1	3	1	4	1	3	1	3	3	4	3	3	1	3	3	2	4	3	2	3	1	3	1	2	2	3	2	30,534
210	1	3	4	3	1	3	3	1	3	3	2	3	4	3	1	2	4	3	1	4	1	3	3	1	1	2	2	4	2	3	3	3	2	3	3	1	3	1	2	2	30,549
211	1	2	1	3	3	1	3	1	4	1	2	2	3	3	4	3	1	3	4	3	4	3	3	3	3	1	3	2	3	1	1	2	3	3	4	1	2	3	2	2	30,565
212	1	4	3	3	4	4	1	3	4	1	3	1	3	3	2	1	3	2	1	3	3	3	1	4	3	3	2	2	1	3	2	3	3	1	3	2	1	2	3	2	30,581
213	1	2	3	1	4	3	4	2	3	3	1	1	1	3	3	3	1	3	4	3	3	3	3	4	1	4	1	3	2	1	3	3	2	2	2	3	2	1	3	2	30,597
214	1	3	4	1	3	3	4	1	3	2	4	3	3	1	4	3	1	3	2	2	3	3	1	1	2	4	2	3	3	3	1	2	3	3	3	1	3	1	2	2	30,613
215	1	1	1	2	2	3	3	3	4	4	3	1	3	3	1	1	3	3	1	3	3	3	4	2	4	2	3	2	1	3	3	4	2	3	3	1	3	2	1	2	30,622
216	1	4	4	4	1	1	3	3	1	2	3	3	1	2	3	2	3	3	3	1	3	1	3	1	3	3	2	4	2	3	3	3	4	2	3	1	3	1	2	2	30,638
217	1	4	2	3	3	3	1	1	4	4	1	1	3	4	3	2	3	3	3	2	3	1	1	3	3	4	2	3	3	1	3	2	1	3	1	3	2	3	2	2	30,661
218	3	1	1	3	2	3	1	3	3	3	4	2	1	1	3	1	1	4	1	3	3	3	4	2	2	3	4	2	3	3	3	4	2	3	3	1	3	1	2	2	30,670
219	1	1	4	4	3	1	1	3	3	2	1	4	2	4	1	3	2	3	3	1	3	3	3	3	3	3	4	2	3	3	3	1	2	1	3	2	3	2	1	2	30,693
220	1	1	4	1	1	3	4	2	3	2	2	3	3	3	3	1	3	3	1	3	4	3	3	1	3	2	3	3	4	1	1	2	4	3	2	3	1	2	3	2	30,708
221	1	1	3	3	2	1	3	4	2	4	3	3	4	3	1	4	1	3	1	3	4	2	3	1	2	3	1	2	3	3	3	3	2	3	1	3	1	3	2	2	30,724
222	3	4	1	3	4	1	3	1	2	1	3	3	4	3	1	3	3	2	2	1	3	3	4	1	3	3	3	1	3	4	2	2	2	3	3	1	3	1	2	2	30,740
223	3	1	3	4	2	4	1	1	3	1	3	3	1	4	3	3	3	3	2	3	1	1	2	4	2	3	3	1	2	3	3	4	3	1	3	1	2	3	2	2	30,749
224	3	3	3	1	4	4	2	1	3	1	1	1	3	1	2	3	2	4	3	4	2	3	3	2	3	1	3	3	3	3	4	1	3	3	1	2	3	2	1	2	30,765
225	1	1	1	3	4	3	1	3	2	2	3	1	3	3	3	4	3	2	3	3	1	4	3	3	4	1	4	1	3	3	1	1	3	2	2	3	2	3	2	2	30,788
226	3	1	3	1	1	3	4	3	3	3	1	2	3	1	1	4	2	2	2	3	1	1	3	4	4	2	3	3	3	3	3	4	3	2	1	3	1	3	2	2	30,797
227	3	1	1	4	2	3	3	3	1	4	3	4	1	3	3	3	1	1	3	3	2	3	3	4	1	1	2	3	2	2	4	1	3	3	3	1	2	3	2	2	30,820
228	1	4	3	3	1	3	1	3	1	3	4	2	4	4	3	1	3	3	2	1	1	3	1	3	3	3	3	2	1	3	1	3	2	4	2	2	3	3	2	2	30,836
229	1	1	1	1	4	3	2	3	1	4	3	1	3	4	2	3	3	3	1	3	3	2	3	1	3	3	2	4	2	3	3	1	4	2	3	3	3	1	2	2	30,845
230	1	1	4	3	1	3	4	1	2	3	4	3	1	1	2	2	3	3	3	1	1	2	3	3	3	4	2	3	3	3	4	3	1	3	1	3	2	3	2	2	30,860

Table 7-31 Sequence, routings and cost estimates of remanufacturing function (19/44)

Test No.	Quality (q)	Distance (km)	Disassembly sequence (by Part Number)																																									
231	0.4	2600	13	32	30	5	14	17	39	9	15	36	11	16	25	40	24	34	23	22	26	20	10	7	27	33	37	38	8	19	4	3	28	29	18	31	35	21	2	6	12
232	0.4	2700	39	14	35	36	34	5	13	30	24	17	32	25	27	23	33	28	38	29	9	15	26	37	19	18	4	21	3	16	31	40	22	11	10	7	20	8	2	6	12
233	0.4	2800	39	5	38	25	35	16	9	15	22	30	36	17	24	13	34	26	11	4	3	21	40	23	14	10	37	20	7	8	19	27	33	32	2	6	28	29	18	12	31
234	0.4	2900	13	16	9	15	14	40	35	32	11	21	5	39	30	25	17	26	23	27	28	10	24	36	7	4	22	20	33	29	38	34	37	3	2	8	6	19	18	31	12
235	0.4	3000	39	24	25	27	28	14	35	9	15	11	40	17	38	5	13	26	10	32	36	7	34	37	21	8	30	33	29	4	16	23	19	3	18	22	31	20	2	6	12
236	0.4	3100	39	16	9	15	22	24	11	38	5	30	40	23	35	17	25	4	21	32	36	34	37	13	3	14	27	26	33	28	19	10	7	29	8	20	18	31	2	6	12
237	0.4	3200	39	30	25	16	5	23	14	9	4	11	15	13	32	36	22	24	17	20	35	21	38	40	26	34	10	27	37	33	3	19	28	29	2	6	18	7	31	12	8
238	0.4	3300	13	14	27	9	15	30	39	32	5	24	40	11	33	35	38	16	21	36	25	34	4	17	37	26	3	22	20	23	28	29	19	10	18	31	2	7	8	6	12
239	0.4	3400	39	9	15	24	16	5	32	22	35	4	25	14	27	33	28	13	21	30	17	20	11	23	29	38	36	34	26	40	10	3	37	2	7	8	6	19	18	31	12
240	0.4	3500	13	25	5	39	35	36	38	9	15	14	4	30	34	32	40	17	24	11	23	16	26	27	28	37	22	3	33	21	20	19	10	2	7	18	8	29	6	12	31
241	0.4	3600	39	38	9	17	30	11	15	32	16	24	36	5	23	4	14	40	13	27	33	35	28	22	21	29	25	34	26	37	20	10	19	18	7	3	8	31	2	6	12
242	0.4	3700	39	14	30	36	16	25	13	34	23	27	38	17	33	28	37	32	9	24	5	29	35	19	11	15	18	4	40	3	31	21	22	20	2	6	26	12	10	7	8
243	0.4	3800	39	9	15	17	40	13	24	38	16	32	11	25	26	14	35	5	10	36	7	4	30	21	22	27	20	23	28	34	33	8	3	29	37	19	18	31	2	6	12
244	0.4	3900	39	24	16	5	17	30	23	14	9	15	36	11	35	38	25	22	34	27	32	28	13	26	40	20	4	21	10	3	37	19	33	29	7	8	2	18	31	6	12
245	0.4	4000	13	35	16	27	17	14	9	15	25	33	26	38	22	11	24	32	10	20	39	40	5	28	4	30	36	7	23	21	29	34	37	3	2	6	8	19	18	31	12
246	0.4	4100	13	38	9	15	11	35	27	16	40	30	23	24	33	28	21	29	36	14	34	37	5	19	4	18	22	32	39	3	31	25	17	20	2	26	6	10	7	8	12
247	0.4	4200	13	14	5	32	39	38	36	17	25	34	27	37	30	28	9	15	23	26	4	35	40	3	21	24	11	10	33	7	29	19	18	31	8	16	22	20	2	6	12
248	0.4	4300	39	14	25	30	24	38	23	16	32	13	27	17	9	28	26	11	15	35	40	33	10	22	29	21	20	36	7	5	4	34	3	2	6	37	19	18	12	8	31
249	0.4	4400	13	32	39	17	24	27	35	16	38	36	5	28	9	15	30	23	14	33	40	21	22	25	11	20	4	29	26	34	37	10	7	8	19	18	3	31	2	6	12
250	0.4	4500	39	25	24	17	5	32	16	35	30	23	9	36	4	34	11	15	14	40	22	38	20	37	19	13	27	18	33	28	29	21	31	3	2	26	10	7	6	12	8
251	0.4	4600	39	25	9	14	24	35	30	36	13	23	5	11	15	16	4	32	21	34	40	3	17	37	27	33	22	28	26	20	2	6	19	10	18	29	7	8	38	31	12
252	0.4	4700	39	16	32	25	5	4	38	14	9	15	35	11	17	30	36	34	22	23	37	21	40	13	27	24	3	28	20	26	33	29	2	10	6	7	19	18	31	12	8
253	0.4	4800	39	16	17	24	13	32	35	27	14	28	9	15	11	21	25	30	36	34	23	5	37	33	40	29	22	4	3	26	19	18	10	38	20	7	31	8	2	6	12
254	0.4	4900	39	32	5	17	9	11	27	35	30	24	33	23	25	13	14	4	26	16	38	10	15	36	7	34	22	3	37	40	19	20	28	18	31	29	21	2	8	6	12
255	0.4	5000	13	36	25	39	24	32	16	9	15	27	40	17	28	22	14	26	38	30	20	23	34	11	5	37	4	3	19	33	18	31	29	10	7	8	35	21	2	6	12

Table 7-32 Sequence, routings and cost estimates of remanufacturing function (20/44)

Test No.	Remanufacturing Method (1=Reuse, 2=Reincarnate, 3=Recycle, 4=Disposal)																																											Cost (£)
231	3	1	1	4	2	3	1	1	3	4	2	1	3	1	3	3	3	3	1	3	2	2	4	3	3	3	3	1	1	4	2	3	3	1	4	3	2	3	2	2	30,883
232	1	2	4	4	3	4	3	1	3	3	1	3	4	3	3	2	3	3	1	3	1	3	1	3	1	3	4	1	1	1	3	2	2	2	3	3	2	3	2	2	30,899
233	1	4	3	3	4	1	1	3	3	1	4	3	3	3	3	1	2	1	4	3	1	3	2	2	3	3	2	3	1	4	3	1	2	3	2	3	3	2	1	2	30,915
234	3	1	1	3	2	1	4	1	2	3	4	1	1	3	3	1	3	4	2	2	3	4	2	1	3	3	3	3	3	3	3	4	2	3	3	1	3	1	2	2	30,924
235	1	3	3	4	2	2	4	1	3	2	1	3	3	4	3	1	2	1	4	2	3	3	3	3	1	3	3	1	1	3	1	4	3	3	1	3	2	3	2	2	30,940
236	1	1	1	3	3	3	2	3	4	1	1	3	4	3	3	1	3	1	4	3	3	3	4	2	4	1	3	2	1	2	2	3	3	3	3	1	2	3	2	2	30,963
237	1	1	3	1	4	3	2	1	1	2	3	3	1	4	3	3	3	3	4	3	3	1	1	3	2	4	3	3	4	1	2	3	2	3	3	2	1	2	3	2	30,979
238	3	2	4	1	3	1	1	1	4	3	1	2	3	4	3	1	3	4	3	3	1	3	3	1	4	3	3	3	2	3	1	2	3	1	2	2	3	3	2	2	30,995
239	1	1	3	3	1	4	1	3	4	1	3	2	4	3	2	3	3	1	3	3	2	3	3	3	4	3	1	1	2	4	3	2	2	3	3	1	3	1	2	2	31,011
240	3	3	4	1	4	4	3	1	3	2	1	1	3	1	1	3	3	2	3	1	1	4	2	3	3	4	3	3	3	1	2	2	2	3	3	3	3	2	1	2	31,026
241	1	3	1	3	1	2	3	1	1	3	4	4	3	1	2	1	3	4	3	4	2	3	3	3	3	3	1	3	3	2	1	3	2	4	3	1	2	3	2	2	31,042
242	1	2	1	4	1	3	3	3	3	4	3	3	3	2	3	1	1	3	4	3	4	1	2	3	3	1	1	4	1	3	3	3	2	3	1	2	2	2	3	2	31,058
243	1	1	3	3	1	3	3	3	1	1	2	3	1	2	4	4	2	4	2	1	1	3	3	4	3	3	2	3	3	3	4	3	3	1	3	1	2	3	2	2	31,067
244	1	3	1	4	3	1	3	2	1	3	4	2	4	3	3	3	3	4	1	2	3	1	1	3	1	3	2	4	3	1	3	3	2	3	2	3	1	3	2	2	31,090
245	3	4	1	4	3	2	1	3	3	3	1	3	3	2	3	1	2	3	1	1	4	2	1	1	4	2	3	3	3	3	3	4	2	3	3	1	3	1	2	2	31,099
246	3	3	1	3	2	4	4	1	1	1	3	3	3	2	3	3	4	2	3	3	4	1	1	3	3	1	1	4	1	3	3	3	2	1	3	2	2	3	2	2	31,122
247	3	2	4	1	1	3	4	3	3	3	4	3	1	2	1	3	3	1	1	4	1	4	3	3	2	2	3	2	3	1	3	1	3	1	3	3	2	3	2	2	31,138
248	1	2	3	1	3	3	3	1	1	3	4	3	1	2	1	2	3	4	1	3	2	3	3	3	3	4	2	4	1	3	4	2	3	3	1	3	2	3	1	2	31,147
249	3	1	1	3	3	4	4	1	3	4	4	2	1	3	1	3	2	3	1	3	3	3	2	3	1	3	1	3	3	2	2	3	1	3	4	1	2	3	2	2	31,170
250	1	3	3	3	4	1	1	4	1	3	1	4	1	3	2	3	2	1	3	3	3	3	1	3	4	3	3	2	3	3	1	4	2	1	2	2	3	2	3	2	31,185
251	1	3	1	2	3	4	1	4	3	3	4	2	3	1	1	1	3	3	1	4	3	3	4	3	3	2	1	3	2	3	1	2	3	3	2	3	3	1	2	2	31,201
252	1	1	1	3	4	1	3	2	1	3	4	2	3	1	4	3	3	3	3	3	1	3	4	3	4	2	3	1	3	3	2	2	3	2	1	3	1	2	3	2	31,217
253	1	1	3	3	3	1	4	4	2	2	1	3	2	3	3	1	4	3	3	4	3	3	1	3	3	1	4	1	1	3	2	3	3	2	1	3	2	3	2	2	31,233
254	1	1	4	3	1	2	4	4	1	3	3	3	3	3	2	1	1	1	3	2	3	4	2	3	3	4	3	1	1	3	2	3	1	3	3	2	3	3	2	2	31,242
255	3	4	3	1	3	1	1	1	3	4	1	3	2	3	2	1	3	1	3	3	3	2	4	3	1	4	1	3	3	1	3	2	2	3	4	3	2	3	2	2	31,265

Table 7-33 Sequence, routings and cost estimates of remanufacturing function (21/44)

Test No.	Quality (q)	Distance (km)	Disassembly sequence (by Part Number)																																										
256	0.5	0	39	27	17	25	14	24	28	30	32	5	35	9	11	15	13	26	23	38	21	33	36	29	34	16	22	37	19	10	4	40	20	18	7	8	3	2	31	6	12
257	0.5	100	39	30	17	23	14	25	5	32	35	13	26	27	28	16	24	38	9	4	11	15	10	21	36	7	22	33	34	29	20	3	37	19	18	2	8	6	31	12	40
258	0.5	200	13	38	36	24	25	27	9	15	28	32	16	35	34	37	11	5	22	39	21	33	40	4	30	14	29	17	20	26	3	10	7	8	23	2	6	19	18	12	31
259	0.5	300	13	39	9	25	27	5	4	17	35	24	38	28	33	14	36	32	16	34	11	3	26	10	15	37	7	30	40	21	29	23	19	18	8	31	22	20	2	6	12
260	0.5	400	39	27	33	28	25	36	35	16	34	5	32	24	14	9	11	15	37	22	21	4	13	17	3	30	20	40	29	2	26	10	7	8	38	6	23	19	18	12	31
261	0.5	500	13	17	16	35	39	30	5	36	9	15	38	14	34	23	4	25	26	37	27	33	24	3	21	19	22	28	20	32	2	29	40	18	11	6	12	31	10	7	8
262	0.5	600	13	39	38	35	27	9	15	17	30	40	25	28	5	32	24	23	4	21	16	14	26	11	10	22	36	7	33	29	20	34	37	19	18	8	3	2	6	12	31
263	0.5	700	13	9	17	24	35	38	32	16	14	5	27	30	25	11	15	26	40	4	23	33	22	20	28	10	21	36	7	34	3	39	29	2	37	19	6	18	31	8	12
264	0.5	800	13	16	14	9	38	39	24	17	11	15	32	40	25	26	35	30	21	22	10	23	27	36	7	5	34	37	4	3	19	18	20	31	33	8	2	6	12	28	29
265	0.5	900	13	14	35	16	17	38	25	27	33	5	9	15	11	4	26	39	22	24	21	10	40	36	7	32	28	30	20	29	23	8	34	3	37	19	2	18	31	6	12
266	0.5	1000	39	27	35	36	34	37	24	32	30	23	13	9	15	28	38	40	25	14	5	16	33	22	11	21	29	19	17	26	10	20	18	7	4	3	8	31	2	6	12
267	0.5	1100	13	30	39	9	15	27	25	16	36	35	21	17	26	40	22	14	32	34	28	24	38	23	20	37	5	19	33	4	11	29	10	7	3	8	2	6	18	31	12
268	0.5	1200	13	38	24	16	9	17	36	34	11	15	30	25	35	39	14	23	40	32	21	22	26	37	27	10	28	5	33	4	7	29	8	19	18	20	3	31	2	6	12
269	0.5	1300	13	14	27	25	35	30	36	33	9	38	23	17	32	26	34	39	11	15	5	24	40	37	28	29	4	3	19	21	18	16	31	10	22	20	7	8	2	6	12
270	0.5	1400	39	24	13	14	25	38	9	15	35	16	36	32	27	17	5	40	28	11	22	20	34	4	37	3	30	21	33	23	2	19	29	26	6	18	12	31	10	7	8
271	0.5	1500	13	27	14	9	28	24	17	16	32	11	15	33	5	22	30	4	39	38	25	23	29	35	26	40	21	10	20	36	7	8	34	3	2	6	37	19	18	31	12
272	0.5	1600	13	14	25	30	16	17	23	26	38	32	9	15	27	33	11	22	39	10	36	7	28	8	35	20	40	24	21	5	34	29	37	4	19	3	18	31	2	6	12
273	0.5	1700	13	38	36	9	34	32	16	11	15	14	30	17	40	22	24	5	35	27	25	37	21	23	39	20	28	4	26	19	3	10	18	7	8	31	33	2	29	6	12
274	0.5	1800	13	27	38	33	24	17	35	39	32	9	28	14	16	11	15	25	21	22	26	40	5	10	30	29	20	23	4	36	7	34	3	8	2	6	37	19	18	31	12
275	0.5	1900	13	38	30	32	23	24	14	27	25	36	34	33	35	39	17	26	9	16	5	4	11	15	37	22	10	19	28	7	18	3	21	40	20	8	2	29	31	6	12
276	0.5	2000	13	27	28	35	9	16	38	39	17	11	15	5	36	25	24	30	14	4	22	32	40	20	34	21	3	26	33	23	10	29	2	37	7	8	19	18	31	6	12
277	0.5	2100	13	17	5	14	9	32	25	39	4	26	11	30	23	38	10	15	36	7	8	27	40	34	16	37	28	3	24	22	20	35	33	29	21	2	6	19	18	31	12
278	0.5	2200	39	25	32	14	5	4	13	16	9	15	38	24	22	30	17	23	20	11	26	27	36	34	35	40	10	21	7	37	33	8	3	2	19	28	6	29	18	12	31
279	0.5	2300	39	35	17	13	5	38	32	27	33	25	26	9	14	24	16	28	11	15	10	22	40	36	7	8	20	21	30	34	23	37	19	29	4	18	3	2	6	12	31
280	0.5	2400	39	5	4	17	24	35	25	36	34	9	14	37	3	16	38	27	30	23	28	11	15	32	19	18	13	22	33	40	31	20	26	10	21	2	7	8	6	29	12
281	0.5	2500	39	35	16	32	14	9	11	15	36	38	22	34	21	30	13	23	17	25	26	20	10	37	7	8	40	27	5	24	19	33	18	4	28	31	29	3	2	6	12

Table 7-34 Sequence, routings and cost estimates of remanufacturing function (22/44)

Test No.	Remanufacturing Method (1=Reuse, 2=Reincarnate, 3=Recycle, 4=Disposal)																																											Cost (£)
256	1	4	3	3	2	3	2	1	1	4	4	1	2	3	3	1	3	3	3	3	4	3	3	1	3	3	1	2	1	1	3	3	2	3	4	2	1	3	2	2	29,379
257	1	1	3	3	2	3	4	1	4	3	1	4	2	1	3	3	1	1	2	3	2	3	4	2	3	3	3	3	3	4	3	1	3	2	3	3	1	2	1	2	29,389
258	3	3	4	3	3	4	1	3	2	1	1	4	3	3	2	4	3	1	3	3	1	1	1	2	3	3	3	1	4	2	2	3	3	2	3	1	3	2	1	2	29,411
259	3	1	1	3	4	4	1	3	4	3	3	2	3	2	4	1	1	3	2	4	1	2	3	3	2	1	1	3	3	3	1	3	3	1	3	3	2	3	2	2	29,427
260	1	4	3	2	3	4	4	1	3	4	1	3	2	1	2	3	3	3	3	1	3	3	4	1	3	1	3	2	1	2	2	3	3	3	3	1	3	2	1	2	29,443
261	3	3	1	4	1	1	4	4	1	3	3	2	3	3	1	3	1	3	4	3	3	4	3	1	3	2	3	1	2	3	1	3	2	3	2	1	2	2	3	2	29,459
262	3	1	3	4	4	1	3	3	1	1	3	2	4	1	3	3	1	3	1	2	1	2	2	3	4	2	3	3	3	3	3	1	3	3	4	2	3	2	1	2	29,468
263	3	1	3	3	4	3	1	1	2	4	4	1	3	2	3	1	1	1	3	3	3	3	2	2	3	4	2	3	4	1	3	2	3	1	3	3	1	3	2	2	29,484
264	3	1	2	1	3	1	3	3	2	3	1	1	3	1	4	1	3	3	2	3	4	4	2	4	3	3	1	4	1	3	3	1	3	3	2	3	2	2	3	2	29,500
265	3	2	4	1	3	3	3	4	3	4	1	3	2	1	1	1	3	3	3	2	1	4	2	1	2	1	3	3	3	3	3	4	3	1	2	3	1	3	2	2	29,516
266	1	4	4	4	3	3	3	1	1	3	3	1	3	2	3	1	3	2	4	1	3	3	2	3	3	1	3	1	2	3	3	2	1	4	3	1	2	3	2	2	29,538
267	3	1	1	1	3	4	3	1	4	4	3	3	1	1	3	2	1	3	2	3	3	3	3	3	4	1	3	1	2	3	2	2	4	3	2	3	3	1	2	2	29,554
268	3	3	3	1	1	3	4	3	2	3	1	3	4	1	2	3	1	1	3	3	1	3	4	2	2	4	3	1	2	3	3	1	3	3	4	1	2	3	2	2	29,570
269	3	2	4	3	4	1	4	3	1	3	3	3	1	1	3	1	2	3	4	3	1	3	2	3	1	4	1	3	3	1	1	2	3	3	2	3	2	3	2	2	29,586
270	1	3	3	2	3	3	1	3	4	1	4	1	4	3	4	1	2	2	3	3	3	1	3	4	1	3	3	3	2	1	3	1	3	3	2	1	2	2	3	2	29,602
271	3	4	2	1	2	3	3	1	1	2	3	3	4	3	1	1	1	3	3	3	3	4	1	1	3	2	3	4	2	3	3	4	2	3	3	1	3	1	2	2	29,611
272	3	2	3	1	1	3	3	1	3	1	1	3	4	3	2	3	1	2	4	2	2	3	4	3	1	3	3	4	3	3	3	1	1	4	3	1	2	3	2	2	29,627
273	3	3	4	1	3	1	1	2	3	2	1	3	1	3	3	4	4	4	3	3	3	3	1	3	2	1	1	1	4	2	3	2	3	1	3	2	3	3	2	2	29,649
274	3	4	3	3	3	3	4	1	1	1	2	2	1	2	3	3	3	3	1	1	4	2	1	3	3	3	1	4	2	3	4	3	2	3	3	1	3	1	2	2	29,659
275	3	3	1	1	3	3	2	4	3	4	3	3	4	1	3	1	1	1	4	1	2	3	3	3	2	1	2	2	3	4	3	1	3	3	2	3	1	3	2	2	29,681
276	3	4	2	4	1	1	3	1	3	2	3	4	4	3	3	1	2	1	3	1	1	3	3	3	4	1	3	3	2	3	2	3	2	3	1	3	1	3	2	2	29,697
277	3	3	4	2	1	1	3	1	1	1	2	1	3	3	2	3	4	2	3	4	1	3	1	3	2	4	3	3	3	4	3	3	3	2	3	1	3	1	2	2	29,707
278	1	3	1	2	4	1	3	1	1	3	3	3	3	1	3	3	3	2	1	4	4	3	4	1	2	3	2	3	3	3	4	2	1	2	3	3	3	2	1	2	29,729
279	1	4	3	3	4	3	1	4	3	3	1	1	2	3	1	2	2	3	2	3	1	4	2	3	3	3	1	3	3	3	1	3	1	3	4	2	3	2	1	2	29,738
280	1	4	1	3	3	4	3	4	3	1	2	3	4	1	3	4	1	3	2	2	3	1	1	3	3	3	3	1	1	3	1	2	3	2	2	3	3	3	2	2	29,761
281	1	4	1	1	2	1	2	3	4	3	3	3	3	1	3	3	3	3	1	3	2	3	2	3	1	4	4	3	1	3	3	1	2	1	3	4	2	3	2	2	29,777

Table 7-35 Sequence, routings and cost estimates of remanufacturing function (23/44)

Test No.	Quality (q)	Distance (km)	Disassembly sequence (by Part Number)																																											
282	0.5	2600	13	39	27	28	14	24	30	5	35	36	32	33	25	34	17	9	15	29	4	3	23	37	40	11	26	19	16	38	18	10	7	21	31	8	22	20	2	6	12					
283	0.5	2700	13	16	14	30	35	32	9	15	17	21	27	22	33	38	23	24	20	25	36	28	5	26	11	4	34	39	37	29	10	3	2	7	19	18	31	40	6	12	8					
284	0.5	2800	13	27	30	25	9	15	17	11	33	35	5	26	23	14	32	21	10	40	24	39	38	16	36	7	8	34	37	22	19	4	3	20	18	31	28	29	2	6	12					
285	0.5	2900	13	24	36	34	38	37	35	5	39	25	9	15	14	27	30	23	28	11	33	40	21	32	29	16	17	19	18	31	26	4	22	20	3	10	2	7	8	6	12					
286	0.5	3000	39	14	38	9	24	30	16	35	25	13	17	23	26	5	11	15	36	32	40	22	34	4	27	10	21	20	28	33	37	3	7	2	29	19	8	6	18	31	12					
287	0.5	3100	39	13	5	24	36	30	35	27	34	25	4	17	26	37	9	15	32	23	40	16	3	38	21	22	14	19	18	33	31	28	11	10	20	29	2	6	7	12	8					
288	0.5	3200	39	5	17	38	27	36	24	30	33	23	13	16	32	9	15	11	34	22	20	35	14	37	28	29	4	21	3	25	2	19	26	18	6	40	12	10	31	7	8					
289	0.5	3300	13	38	14	32	36	34	27	5	37	24	39	35	17	9	25	16	26	33	30	11	15	28	21	23	40	19	29	18	4	31	22	20	10	7	3	2	6	8	12					
290	0.5	3400	39	17	35	16	30	5	27	9	11	15	25	21	24	38	22	20	4	14	33	40	36	13	32	26	10	23	34	3	37	19	7	18	31	2	8	6	12	28	29					
291	0.5	3500	13	14	24	25	27	9	15	39	30	33	36	38	11	17	34	26	5	16	4	23	3	22	37	40	35	10	21	20	2	28	6	29	19	7	8	32	18	31	12					
292	0.5	3600	39	9	24	36	13	30	34	11	15	32	17	27	14	38	25	35	37	40	5	21	4	33	23	16	19	28	26	10	18	22	20	31	3	7	2	6	29	12	8					
293	0.5	3700	39	17	5	13	30	35	27	33	23	32	14	9	4	11	15	16	21	38	24	22	40	20	28	29	25	26	10	36	7	34	37	8	3	19	18	2	6	31	12					
294	0.5	3800	39	14	16	32	17	13	9	15	38	27	36	33	34	22	11	25	20	40	28	37	26	5	4	3	35	24	30	29	10	21	23	19	2	18	31	7	8	6	12					
295	0.5	3900	13	35	17	30	36	34	32	27	38	28	33	25	39	26	37	29	23	9	15	24	16	22	21	14	11	19	40	10	18	31	20	5	7	8	4	3	2	6	12					
296	0.5	4000	39	36	32	17	9	11	15	13	16	35	30	21	40	22	5	23	27	24	38	25	26	20	28	33	4	14	29	34	37	10	3	7	2	8	6	19	18	12	31					
297	0.5	4100	13	27	17	33	32	25	14	9	15	16	24	40	26	11	38	28	30	5	39	29	35	10	21	36	7	8	23	34	4	37	19	22	3	20	2	18	6	12	31					
298	0.5	4200	39	16	25	27	5	35	13	33	30	24	14	32	28	23	9	15	29	40	17	22	26	21	11	38	20	10	36	7	34	4	3	37	19	2	6	8	18	31	12					
299	0.5	4300	13	14	27	9	15	30	17	38	39	28	23	16	33	5	35	29	11	25	32	26	10	36	7	34	4	21	40	22	3	37	24	19	8	18	31	20	2	6	12					
300	0.5	4400	39	9	27	36	34	5	33	38	24	11	15	14	4	28	25	40	32	13	16	37	22	17	20	35	3	21	30	26	23	10	2	29	7	8	6	19	18	31	12					
301	0.5	4500	13	14	35	38	39	9	32	17	25	11	15	36	24	16	34	40	37	22	20	5	26	21	4	3	30	27	10	33	7	28	23	8	19	29	18	2	31	6	12					
302	0.5	4600	39	24	17	32	27	9	36	5	34	33	25	37	38	11	15	30	13	16	28	40	22	23	29	14	19	26	20	18	10	7	35	4	31	3	21	8	2	6	12					
303	0.5	4700	13	17	24	5	25	26	35	36	38	34	16	14	9	4	37	3	30	11	23	19	18	32	27	28	33	29	10	15	31	7	8	21	39	40	22	20	2	6	12					
304	0.5	4800	13	14	17	16	32	5	25	38	9	4	26	11	35	30	24	39	10	15	36	7	23	27	22	33	34	21	20	37	28	19	18	3	8	29	40	2	6	31	12					
305	0.5	4900	13	32	9	39	5	38	35	25	14	16	4	11	17	27	24	33	26	10	15	28	22	36	7	20	40	8	21	30	34	23	37	3	29	2	19	18	31	6	12					
306	0.5	5000	13	27	25	9	15	14	17	16	22	40	32	39	26	35	5	20	38	21	33	11	30	10	4	28	36	7	34	3	8	29	37	2	24	6	23	19	18	12	31					

Table 7-36 Sequence, routings and cost estimates of remanufacturing function (24/44)

Test No.	Remanufacturing Method (1=Reuse, 2=Reincarnate, 3=Recycle, 4=Disposal)																																											Cost (£)
282	3	1	4	2	2	3	1	4	4	4	1	3	3	3	3	1	3	3	1	4	3	3	1	2	1	1	1	3	3	2	2	3	1	3	3	3	2	3	2	2	29,793
283	3	1	2	1	4	1	1	3	3	3	4	3	3	3	3	3	3	3	4	2	4	1	2	1	3	1	3	3	2	4	2	2	1	3	1	1	3	2	3	2	29,808
284	3	4	1	3	1	3	3	2	3	4	4	1	3	2	1	3	2	1	3	1	3	1	4	2	3	3	3	3	1	1	4	3	3	1	2	3	2	3	2	2	29,818
285	3	3	4	3	3	3	4	4	1	3	1	3	2	4	1	3	2	2	3	1	3	1	3	1	3	1	3	1	1	1	3	3	4	2	2	2	3	3	2	2	29,840
286	1	2	3	1	3	1	1	4	3	3	3	3	1	4	2	3	4	1	1	3	3	1	4	2	3	3	2	3	3	4	2	2	3	1	3	3	3	1	2	2	29,856
287	1	3	4	3	4	1	4	4	3	3	1	3	1	3	1	3	1	3	1	1	4	3	3	3	2	1	3	3	1	2	2	2	3	3	2	3	2	2	3	2	29,872
288	1	4	3	3	4	4	3	1	3	3	3	1	1	1	3	2	3	3	3	4	2	3	2	3	1	3	4	3	2	1	1	3	3	1	2	2	1	2	3	2	29,888
289	3	3	2	1	4	3	4	4	3	3	1	4	3	1	3	1	1	3	1	2	3	2	3	3	1	1	3	3	1	1	3	3	2	2	4	2	3	3	2	2	29,904
290	1	3	4	1	1	4	4	1	2	3	3	3	3	3	3	3	1	2	3	1	4	3	1	1	2	3	3	4	3	1	2	3	1	2	3	3	2	2	3	2	29,920
291	3	2	3	3	4	1	3	1	1	3	4	3	2	3	3	1	4	1	1	3	4	3	3	1	4	2	3	3	2	2	3	3	1	2	3	1	3	1	2	2	29,936
292	1	1	3	4	3	1	3	2	3	1	3	4	2	3	3	4	3	1	4	3	1	3	3	1	1	2	1	2	3	3	3	1	4	2	2	3	3	2	3	2	29,952
293	1	3	4	3	1	4	4	3	3	1	2	1	1	2	3	1	3	3	3	3	1	3	2	3	3	1	2	4	2	3	3	3	4	1	3	2	3	1	2	2	29,961
294	1	2	1	1	3	3	1	3	3	4	4	3	3	3	2	3	3	1	2	3	1	4	1	4	4	3	1	3	2	3	3	1	2	3	1	2	3	3	2	2	29,983
295	3	4	3	1	4	3	1	4	3	2	3	3	1	1	3	3	3	1	3	3	1	3	3	2	2	1	1	2	3	1	3	4	2	3	1	4	2	3	2	2	29,999
296	1	4	1	3	1	2	3	3	1	4	1	3	1	3	4	3	4	3	3	3	1	3	2	3	1	2	3	3	3	2	4	2	2	3	3	1	3	2	1	2	30,015
297	3	4	3	3	1	3	2	1	3	1	3	1	1	2	3	2	1	4	1	3	4	2	3	4	2	3	3	3	1	3	1	3	4	3	2	3	3	2	1	2	30,025
298	1	1	3	4	4	4	3	3	1	3	2	1	2	3	1	3	3	1	3	3	1	3	2	3	3	2	4	2	3	1	4	3	1	2	3	3	3	1	2	2	30,040
299	3	2	4	1	3	1	3	3	1	2	3	1	3	4	4	3	2	3	1	1	2	4	2	3	1	3	1	3	4	3	3	1	3	3	1	3	2	3	2	2	30,056
300	1	1	4	4	3	4	3	3	3	2	3	2	1	2	3	1	1	3	1	3	3	3	3	4	4	3	1	1	3	2	2	3	2	3	3	1	3	1	2	2	30,079
301	3	2	4	3	1	1	1	3	3	2	3	4	3	1	3	1	3	3	3	4	1	3	1	4	1	4	2	3	2	2	3	3	1	3	3	2	1	3	2	2	30,095
302	1	3	3	1	4	1	4	4	3	3	3	3	3	2	3	1	3	1	2	1	3	3	3	2	1	1	3	3	2	2	4	1	1	4	3	3	2	3	2	2	30,111
303	3	3	3	4	3	1	4	4	3	3	1	2	1	1	3	4	1	2	3	1	3	1	4	2	3	3	2	3	1	2	3	3	1	1	3	3	2	3	2	2	30,126
304	3	2	3	1	1	4	3	3	1	1	1	2	4	1	3	1	2	3	4	2	3	4	3	3	3	3	3	3	2	1	3	4	3	3	1	2	3	1	2	2	30,136
305	3	1	1	1	4	3	4	3	2	1	1	2	3	4	3	3	1	2	3	2	3	4	2	3	1	3	3	1	3	3	3	4	3	2	1	3	1	3	2	2	30,152
306	3	4	3	1	3	2	3	1	3	1	1	1	1	4	4	3	3	3	3	2	1	2	1	2	4	2	3	4	3	3	3	2	3	3	3	1	3	2	1	2	30,168

Table 7-37 Sequence, routings and cost estimates of remanufacturing function (25/44)

Test No.	Quality (q)	Distance (km)	Disassembly sequence (by Part Number)																																											
307	0.6	0	39	16	30	25	24	38	14	32	17	9	27	35	36	33	13	23	28	11	15	22	20	5	21	34	40	37	26	10	4	3	29	2	6	7	8	19	18	12	31
308	0.6	100	39	14	5	9	24	32	17	35	30	27	11	15	13	25	16	4	36	33	34	28	37	29	38	3	23	19	22	21	18	26	10	20	40	7	8	2	31	6	12
309	0.6	200	39	16	14	30	13	23	9	32	5	36	24	25	17	34	38	35	11	15	22	21	26	40	4	3	20	37	10	7	8	19	18	27	28	33	2	6	31	12	29
310	0.6	300	13	36	17	24	35	32	34	30	39	9	15	14	16	22	40	37	38	27	11	23	25	21	19	20	33	26	10	18	31	7	5	4	3	8	2	28	29	6	12
311	0.6	400	13	36	5	27	28	4	16	25	14	38	32	39	33	9	11	15	35	34	21	24	30	40	37	29	3	22	17	20	23	26	2	6	19	18	12	31	10	7	8
312	0.6	500	13	9	15	36	16	17	5	4	34	3	11	37	27	30	24	38	35	32	28	21	23	39	22	40	33	29	14	20	2	6	25	26	19	10	7	18	12	8	31
313	0.6	600	13	27	9	11	15	38	17	25	40	35	14	24	32	28	26	39	10	36	7	21	34	8	5	33	30	16	37	29	23	19	18	4	22	20	31	3	2	6	12
314	0.6	700	39	35	32	24	9	15	11	30	16	13	38	40	23	27	33	21	14	25	22	17	20	28	26	29	5	4	10	36	7	8	34	37	3	19	18	2	31	6	12
315	0.6	800	13	16	30	17	23	14	36	39	9	15	35	5	24	34	27	28	37	11	33	29	32	19	21	40	25	18	38	31	4	3	26	22	10	7	20	2	8	6	12
316	0.6	900	39	36	27	24	30	17	23	28	16	5	9	4	14	34	38	3	11	15	25	32	35	22	13	26	40	20	37	21	19	18	33	29	31	2	10	7	8	6	12
317	0.6	1000	39	24	32	13	14	16	25	27	38	33	5	4	9	15	17	26	30	40	35	36	21	34	11	28	23	3	29	10	7	37	22	8	20	2	6	19	18	31	12
318	0.6	1100	13	35	9	15	14	39	11	36	21	24	30	34	25	27	5	33	28	4	32	23	40	17	37	38	29	19	26	16	3	18	22	10	7	20	2	6	8	31	12
319	0.6	1200	39	17	14	16	13	25	5	27	9	26	11	15	38	10	24	28	30	33	23	35	36	7	32	22	40	34	29	8	4	3	21	37	19	20	18	2	6	31	12
320	0.6	1300	39	32	25	36	27	16	9	15	11	13	40	35	30	21	5	22	14	4	38	34	33	37	23	17	20	26	24	3	19	10	2	28	7	6	18	31	12	8	29
321	0.6	1400	39	9	15	27	30	11	25	40	38	17	13	36	5	16	34	33	14	28	22	37	20	35	29	4	32	23	21	24	26	19	18	31	3	2	10	6	12	7	8
322	0.6	1500	13	38	27	35	16	17	9	14	24	25	33	11	28	5	4	39	26	10	15	32	36	7	30	34	23	37	19	21	22	29	3	20	40	18	2	31	8	6	12
323	0.6	1600	13	39	17	5	16	25	9	15	27	11	35	40	33	30	4	21	22	38	23	26	32	24	20	14	10	28	29	36	7	34	37	8	3	2	19	6	18	12	31
324	0.6	1700	13	32	14	5	30	27	35	39	24	28	38	23	17	9	15	33	29	4	11	21	16	25	36	34	40	22	3	20	2	6	26	37	10	19	18	12	31	7	8
325	0.6	1800	39	17	5	32	38	30	4	16	25	14	9	11	15	24	23	35	27	28	22	13	21	33	29	20	26	10	40	36	7	8	34	3	2	6	37	19	18	12	31
326	0.6	1900	39	14	9	15	13	35	25	16	30	17	11	26	24	38	22	32	20	40	21	10	36	7	5	23	8	4	34	3	37	19	27	28	33	18	31	29	2	6	12
327	0.6	2000	39	16	14	24	27	35	38	36	5	28	17	30	9	15	22	33	11	13	29	23	34	20	40	25	21	4	3	37	32	26	10	2	19	6	7	18	31	8	12
328	0.6	2100	39	30	25	27	14	23	35	13	33	32	9	15	11	38	40	17	21	5	28	29	26	10	36	7	24	8	4	34	3	37	16	22	20	19	2	6	18	12	31
329	0.6	2200	39	38	35	17	5	14	36	25	30	9	15	24	4	40	23	13	27	28	33	34	21	29	16	3	26	11	22	32	20	10	2	6	37	19	7	8	18	31	12
330	0.6	2300	39	36	17	13	24	9	30	14	27	38	5	32	33	25	4	16	35	23	11	15	22	20	34	40	3	28	29	37	21	19	18	26	2	31	6	12	10	7	8
331	0.6	2400	13	27	38	32	35	24	9	25	17	26	5	11	15	28	21	33	36	14	30	16	23	34	4	3	37	29	40	39	22	10	19	20	2	18	31	7	8	6	12
332	0.6	2500	13	39	9	36	17	11	15	35	40	16	25	24	30	34	27	23	37	33	21	32	26	14	38	10	22	5	20	19	4	18	28	31	7	29	3	2	8	6	12

Table 7-38 Sequence, routings and cost estimates of remanufacturing function (26/44)

Test No.	Remanufacturing Method (1=Reuse, 2=Reincarnate, 3=Recycle, 4=Disposal)																																										Cost (£)
307	1	1	1	3	3	3	2	1	3	1	4	4	4	3	3	3	2	2	3	3	3	4	3	3	1	3	1	2	1	4	3	2	3	2	3	1	3	2	1	2	28,288
308	1	2	4	1	3	1	3	4	1	4	2	3	3	3	1	1	4	3	3	2	3	3	3	4	3	1	3	3	3	1	2	3	1	2	3	2	1	3	2	2	28,304
309	1	1	2	1	3	3	1	1	4	4	3	3	3	3	3	4	2	3	3	3	1	1	1	4	3	3	2	2	3	1	3	4	2	3	2	3	1	2	3	2	28,320
310	3	4	3	3	4	1	3	1	1	1	3	2	1	3	1	3	3	4	2	3	3	3	1	3	3	1	2	3	1	2	4	1	4	3	2	2	3	3	2	2	28,336
311	3	4	4	4	2	1	1	3	2	3	1	1	3	1	2	3	4	3	3	3	1	1	3	3	4	3	3	3	3	1	2	3	1	3	2	1	2	2	3	2	28,352
312	3	1	3	4	1	3	4	1	3	4	2	3	4	1	3	3	4	1	2	3	3	1	3	1	3	3	2	3	2	3	3	1	1	2	2	3	2	3	1	2	28,368
313	3	4	1	2	3	3	3	3	1	4	2	3	1	2	1	1	2	4	2	3	3	3	4	3	1	1	3	3	3	1	3	1	3	3	1	4	2	3	2	2	28,378
314	1	4	1	3	1	3	2	1	1	3	3	1	3	4	3	3	2	3	3	3	3	2	1	3	4	1	2	4	2	3	3	3	4	1	3	2	1	3	2	2	28,394
315	3	1	1	3	3	2	4	1	1	3	4	4	3	3	4	2	3	2	3	3	1	1	3	1	3	3	3	1	1	4	1	3	2	2	3	2	3	3	2	2	28,416
316	1	4	4	3	1	3	3	2	1	4	1	1	2	3	3	4	2	3	3	1	4	3	3	1	1	3	3	3	1	3	3	3	1	2	2	2	3	3	2	2	28,431
317	1	3	1	3	2	1	3	4	3	3	4	1	1	3	3	1	1	1	4	4	3	3	2	2	3	4	3	2	2	3	3	3	3	2	3	1	3	1	2	2	28,447
318	3	4	1	3	2	1	2	4	3	3	1	3	3	4	4	3	2	1	1	3	1	3	3	3	3	1	1	1	4	3	3	2	2	3	2	3	3	1	2	2	28,463
319	1	3	2	1	3	3	4	4	1	1	2	3	3	2	3	2	1	3	3	4	4	2	1	3	1	3	3	3	1	4	3	3	1	3	3	2	3	1	2	2	28,473
320	1	1	3	4	4	1	1	3	2	3	1	4	1	3	4	3	2	1	3	3	3	3	3	3	3	1	3	4	1	2	2	2	2	3	3	1	2	3	3	2	28,495
321	1	1	3	4	1	2	3	1	3	3	3	4	4	1	3	3	2	2	3	3	3	4	3	1	1	3	3	3	1	1	3	1	4	2	2	3	2	2	3	2	28,511
322	3	3	4	4	1	3	1	2	3	3	3	2	2	4	1	1	1	2	3	1	4	2	1	3	3	3	1	3	3	3	4	3	1	3	2	1	3	3	2	2	28,521
323	3	1	3	4	1	3	1	3	4	2	4	1	3	1	1	3	3	3	3	1	1	3	3	2	2	2	3	4	2	3	3	3	4	2	1	3	3	2	1	2	28,537
324	3	1	2	4	1	4	4	1	3	2	3	3	3	1	3	3	3	1	2	3	1	3	4	3	1	3	4	3	2	3	1	3	2	1	3	2	1	2	3	2	28,559
325	1	3	4	1	3	1	1	1	3	2	1	2	3	3	3	4	4	2	3	3	3	3	3	3	1	2	1	4	2	3	3	4	2	3	3	1	3	2	1	2	28,568
326	1	2	1	3	3	4	3	1	1	3	2	1	3	3	3	1	3	1	3	2	4	2	4	3	3	1	3	4	3	1	4	2	3	3	1	3	2	3	2	2	28,584
327	1	1	2	3	4	4	3	4	4	2	3	1	1	3	3	3	2	3	3	3	3	3	1	3	3	1	4	3	1	1	2	2	1	3	2	3	1	3	2	2	28,606
328	1	1	3	4	2	3	4	3	3	1	1	3	2	3	1	3	3	4	2	3	1	2	4	2	3	3	1	3	4	3	1	3	3	1	2	3	3	2	1	2	28,616
329	1	3	4	3	4	2	4	3	1	1	3	3	1	1	3	3	4	2	3	3	3	3	1	4	1	2	3	1	3	2	2	3	3	1	2	3	3	1	2	2	28,638
330	1	4	3	3	3	1	1	2	4	3	4	1	3	3	1	1	4	3	2	3	3	3	3	1	4	2	3	3	3	1	3	1	2	1	3	2	2	2	3	2	28,654
331	3	4	3	1	4	3	1	3	3	1	4	2	3	2	3	3	4	2	1	1	3	3	1	4	3	3	1	1	3	2	1	3	2	3	1	2	3	3	2	2	28,670
332	3	1	1	4	3	2	3	4	1	1	3	3	1	3	4	3	3	3	3	1	1	2	3	2	3	4	3	1	1	3	2	1	2	3	4	2	3	3	2	2	28,686

Table 7-39 Sequence, routings and cost estimates of remanufacturing function (27/44)

Test No.	Quality (q)	Distance (km)	Disassembly sequence (by Part Number)																																											
333	0.6	2600	13	5	9	14	39	35	38	25	27	32	4	30	28	24	11	15	17	33	26	23	10	16	22	36	7	20	29	40	21	34	37	3	2	8	6	19	18	31	12
334	0.6	2700	13	25	30	16	32	9	15	11	23	24	38	40	27	17	26	35	28	39	14	10	21	22	20	5	36	7	34	37	4	33	19	3	29	18	31	8	2	6	12
335	0.6	2800	39	38	30	24	13	9	23	25	17	16	35	14	26	11	15	10	36	7	32	5	27	8	40	28	22	20	21	34	33	4	3	29	2	6	37	19	18	12	31
336	0.6	2900	13	5	16	9	15	39	30	25	17	26	40	38	23	32	14	11	35	24	27	36	21	4	28	34	37	19	22	18	20	31	3	10	7	8	33	2	6	12	29
337	0.6	3000	39	25	17	16	24	36	35	14	34	5	30	23	38	9	15	11	27	4	28	21	32	3	33	29	37	22	13	40	20	19	2	18	6	26	31	10	12	7	8
338	0.6	3100	13	36	17	27	5	24	14	9	11	16	34	35	37	4	30	3	33	25	28	38	39	26	10	15	7	21	22	8	20	29	23	40	2	6	32	19	18	12	31
339	0.6	3200	13	5	38	36	27	34	9	28	25	17	37	24	14	35	39	30	11	15	16	21	32	23	4	3	33	40	19	22	20	26	29	18	10	7	2	8	6	31	12
340	0.6	3300	13	27	17	39	38	28	5	24	14	33	4	36	32	25	16	26	9	34	3	35	11	15	22	37	21	10	7	8	40	20	2	30	29	6	23	19	18	12	31
341	0.6	3400	13	5	4	17	38	25	26	36	27	35	16	32	30	33	14	28	9	11	34	24	3	29	37	23	10	15	39	21	7	8	19	18	40	31	22	20	2	6	12
342	0.6	3500	13	25	9	32	5	27	35	38	17	16	11	15	39	28	14	30	24	22	26	4	10	21	40	20	23	36	7	33	29	34	37	19	8	3	2	18	31	6	12
343	0.6	3600	13	24	32	9	30	14	11	15	25	16	35	27	5	17	39	4	23	36	28	34	38	40	21	33	29	26	10	22	7	8	3	20	2	6	37	19	18	12	31
344	0.6	3700	39	38	9	15	13	16	5	14	30	24	35	25	32	22	17	26	23	40	20	11	21	10	27	28	4	36	7	34	33	29	8	3	37	2	6	19	18	12	31
345	0.6	3800	13	24	32	14	5	9	15	16	35	21	22	39	38	4	36	30	17	20	25	11	40	34	23	37	27	26	19	28	18	10	7	33	3	29	2	6	31	12	8
346	0.6	3900	39	16	35	30	17	9	15	13	40	38	24	21	5	22	36	11	27	33	34	14	20	37	28	32	4	29	3	25	2	23	6	19	26	10	18	12	31	7	8
347	0.6	4000	13	25	16	36	9	15	17	39	30	35	40	21	32	26	27	22	11	23	14	34	37	10	38	33	24	7	8	20	28	19	29	18	5	31	4	3	2	6	12
348	0.6	4100	13	24	9	15	27	38	32	28	30	25	5	4	33	40	29	11	17	16	23	35	22	20	21	39	26	14	10	36	7	8	34	37	19	3	18	31	2	6	12
349	0.6	4200	39	5	27	36	34	35	28	13	24	33	4	9	15	16	22	3	38	30	37	40	14	32	21	23	25	29	11	19	18	31	17	26	10	20	2	7	6	8	12
350	0.6	4300	13	16	32	9	27	30	39	36	23	34	14	38	33	24	35	25	28	5	11	15	37	22	21	19	40	18	4	17	20	3	2	29	31	26	10	6	7	8	12
351	0.6	4400	39	36	16	17	14	32	25	38	5	30	9	15	34	40	11	37	35	13	23	27	4	22	33	24	3	19	26	28	18	21	10	20	31	7	2	29	8	6	12
352	0.6	4500	39	30	25	13	17	35	16	23	9	15	38	26	14	5	4	21	11	32	22	20	10	27	24	36	7	28	8	34	3	40	33	37	29	19	18	31	2	6	12
353	0.6	4600	13	17	25	32	26	16	5	30	23	24	9	4	27	39	28	35	11	15	33	14	10	38	29	22	7	8	20	36	40	34	21	3	37	2	19	6	18	12	31
354	0.6	4700	39	25	38	13	5	36	9	15	17	34	16	37	4	27	11	33	14	24	28	32	30	29	23	40	3	22	20	19	35	26	10	21	18	2	7	31	8	6	12
355	0.6	4800	39	17	38	9	11	15	25	16	14	35	21	32	30	22	23	5	24	13	4	40	26	27	10	36	7	33	8	20	34	3	2	28	29	37	6	19	18	12	31
356	0.6	4900	39	16	24	9	13	35	14	36	11	38	17	5	32	25	34	30	37	26	27	23	10	15	33	22	4	40	28	19	7	20	18	8	31	3	21	29	2	6	12
357	0.6	5000	13	14	16	32	5	25	39	17	9	15	11	40	30	38	23	24	35	26	10	27	22	21	4	36	7	34	37	3	19	20	33	18	2	8	28	6	12	31	29

Table 7-40 Sequence, routings and cost estimates of remanufacturing function (28/44)

Test No.	Remanufacturing Method (1=Reuse, 2=Reincarnate, 3=Recycle, 4=Disposal)																																									Cost (£)
333	3	4	1	2	1	4	3	3	4	1	1	1	2	3	2	3	3	3	1	3	2	1	3	4	2	3	3	1	3	3	3	4	2	3	3	1	3	1	2	2	28,696
334	3	3	1	1	1	1	3	2	3	3	3	1	4	3	1	4	2	1	2	2	3	3	3	4	4	2	3	3	1	3	1	4	3	3	1	3	2	3	2	2	28,712
335	1	3	1	3	3	1	3	3	3	1	4	2	1	2	3	2	4	2	1	4	4	3	1	2	3	3	3	3	3	1	4	3	2	3	3	1	3	2	1	2	28,727
336	3	4	1	1	3	1	1	3	3	1	1	3	3	1	2	2	4	3	4	4	3	1	2	3	3	1	3	3	3	1	4	2	2	3	3	2	3	2	3	2	28,749
337	1	3	3	1	3	4	4	2	3	4	1	3	3	1	3	2	4	1	2	3	1	4	3	3	3	3	3	1	3	1	2	3	3	1	1	2	2	2	3	2	28,765
338	3	4	3	4	4	3	2	1	2	1	3	4	3	1	1	4	3	3	2	3	1	1	2	3	2	3	3	3	3	3	3	1	2	3	1	1	3	2	1	2	28,781
339	3	4	3	4	4	3	1	2	3	3	3	3	2	4	1	1	2	3	1	3	1	3	1	4	3	1	1	3	3	1	3	3	2	2	2	3	3	1	2	2	28,797
340	3	4	3	1	3	2	4	3	2	3	1	4	1	3	1	1	1	3	4	4	2	3	3	3	3	2	2	3	1	3	2	1	3	3	3	1	3	2	1	2	28,813
341	3	4	1	3	3	3	1	4	4	4	1	1	1	3	2	2	1	2	3	3	4	3	3	3	2	3	1	3	2	3	1	3	1	1	3	3	2	3	2	2	28,829
342	3	3	1	1	4	4	4	3	3	1	2	3	1	2	2	1	3	3	1	1	2	3	1	3	3	4	2	3	3	3	3	1	3	4	2	3	1	3	2	2	28,839
343	3	3	1	1	1	2	2	3	3	1	4	4	4	3	1	1	3	4	2	3	3	1	3	3	3	1	2	3	2	3	4	3	2	3	3	1	3	2	1	2	28,861
344	1	3	1	3	3	1	4	2	1	3	4	3	1	3	3	1	3	1	3	2	3	2	4	2	1	4	2	3	3	3	3	4	3	2	3	1	3	2	1	2	28,871
345	3	3	1	2	4	1	3	1	4	3	3	1	3	1	4	1	3	3	3	2	1	3	3	3	4	1	1	2	3	2	2	3	4	3	2	3	1	2	3	2	28,893
346	1	1	4	1	3	1	3	3	1	3	3	3	4	3	4	2	4	3	3	2	3	3	2	1	1	3	4	3	2	3	3	1	1	2	3	2	1	2	3	2	28,908
347	3	3	1	4	1	3	3	1	1	4	1	3	1	1	4	3	2	3	2	3	3	2	3	3	3	2	3	3	2	1	3	3	4	1	1	4	2	3	2	2	28,924
348	3	3	1	3	4	3	1	2	1	3	4	1	3	1	3	2	3	1	3	4	3	3	3	1	1	2	2	4	2	3	3	3	1	4	3	1	2	3	2	2	28,934
349	1	4	4	4	3	4	2	3	3	3	1	1	3	1	3	4	3	1	3	1	2	1	3	3	3	3	2	1	3	1	3	1	2	3	2	2	3	3	2	2	28,956
350	3	1	1	1	4	1	1	4	3	3	2	3	3	3	4	3	2	4	2	3	3	3	3	1	1	3	1	3	3	4	2	3	1	1	2	3	2	3	2	2	28,972
351	1	4	1	3	2	1	3	3	4	1	1	3	3	1	2	3	4	3	3	4	1	3	3	3	4	1	1	2	3	3	2	3	1	2	2	3	3	3	2	2	28,988
352	1	1	3	3	3	4	1	3	1	3	3	1	2	4	1	3	2	1	3	3	2	4	3	4	2	2	3	3	4	1	3	3	3	1	3	1	2	3	2	2	28,998
353	3	3	3	1	1	1	4	1	3	3	1	1	4	1	2	4	2	3	3	2	2	3	3	3	2	3	3	4	1	3	3	4	3	2	1	3	3	2	1	2	29,020
354	1	3	3	3	4	4	1	3	3	3	1	3	1	4	2	3	2	3	2	1	1	3	3	1	4	3	3	1	4	1	2	3	3	2	2	1	3	3	2	2	29,036
355	1	3	3	1	2	3	3	1	2	4	3	1	1	3	3	4	3	3	1	1	1	4	2	4	2	3	3	3	3	4	2	2	3	3	3	1	3	2	1	2	29,045
356	1	1	3	1	3	4	2	4	2	3	3	4	1	3	3	1	3	1	4	3	2	3	3	3	1	1	2	1	2	3	3	3	1	4	3	3	2	3	2	2	29,067
357	3	2	1	1	4	3	1	3	1	3	2	1	1	3	3	3	4	1	2	4	3	3	1	4	2	3	3	4	1	3	3	3	2	3	2	3	2	1	3	2	29,077

Table 7-41 Sequence, routings and cost estimates of remanufacturing function (29/44)

Test No.	Quality (q)	Distance (km)	Disassembly sequence (by Part Number)																																									
358	0.7	0	13	5	35	17	24	16	9	39	36	11	15	27	30	38	28	4	23	21	14	40	25	26	22	10	33	34	37	7	8	32	20	3	19	29	2	18	31	6	12
359	0.7	100	39	16	17	14	32	13	24	9	15	30	25	5	27	28	35	33	23	21	26	11	29	4	40	22	10	36	7	38	8	34	20	3	2	37	6	19	18	31	12
360	0.7	200	39	14	27	9	36	34	35	33	30	23	38	24	11	15	17	21	13	37	16	25	32	28	19	5	26	10	29	4	3	7	22	20	40	2	6	18	31	12	8
361	0.7	300	13	38	14	17	16	32	39	30	9	24	23	27	33	28	36	29	35	25	26	11	15	10	34	5	22	20	7	21	4	40	3	8	2	37	19	18	6	31	12
362	0.7	400	39	9	15	27	25	36	33	35	5	28	34	4	21	37	38	16	32	11	30	23	17	3	40	14	29	22	13	26	20	24	19	18	2	6	31	12	10	7	8
363	0.7	500	39	14	24	35	13	17	27	16	38	9	25	30	11	15	28	5	21	40	33	32	36	34	37	4	3	23	22	26	10	20	19	2	18	6	12	7	8	31	29
364	0.7	600	39	13	35	30	16	5	17	4	25	38	14	36	34	27	9	15	26	28	32	3	40	37	33	29	11	21	24	10	7	8	22	20	2	6	23	19	18	31	12
365	0.7	700	39	9	30	38	14	13	23	27	17	33	28	24	25	32	35	26	16	11	15	5	21	22	4	29	20	36	34	40	10	37	7	8	3	19	18	31	2	6	12
366	0.7	800	13	24	30	38	5	25	35	9	15	11	16	14	22	32	4	17	20	26	10	27	23	21	39	40	36	7	34	8	33	28	3	29	37	2	19	18	6	31	12
367	0.7	900	39	25	36	35	9	16	24	11	15	30	40	32	34	21	27	14	37	23	5	22	28	33	17	13	19	20	29	4	26	18	31	3	38	2	6	10	7	12	8
368	0.7	1000	13	38	32	9	15	14	27	17	35	28	30	5	25	33	39	29	21	11	16	4	40	26	24	10	36	7	34	8	22	23	3	20	37	2	19	6	18	12	31
369	0.7	1100	13	25	36	39	14	30	16	27	9	5	34	37	28	17	35	11	15	26	21	22	38	32	33	4	29	3	40	10	23	7	20	24	19	2	18	6	8	12	31
370	0.7	1200	13	30	35	23	9	15	27	33	5	11	17	24	40	25	14	38	28	39	32	16	4	21	26	29	22	10	36	7	20	8	34	37	3	2	6	19	18	12	31
371	0.7	1300	39	14	13	25	35	17	5	32	9	15	30	26	40	11	27	10	28	33	16	24	23	21	38	4	36	7	8	29	22	20	34	3	2	6	37	19	18	12	31
372	0.7	1400	13	35	17	38	16	14	39	5	25	27	30	9	15	36	24	40	33	4	34	23	11	3	32	37	28	29	19	22	26	10	18	20	21	31	7	2	8	6	12
373	0.7	1500	39	5	9	15	38	17	40	35	21	14	25	16	27	24	32	30	22	20	4	11	13	28	23	33	29	26	10	36	7	8	34	37	19	3	18	31	2	6	12
374	0.7	1600	39	30	24	25	36	13	34	14	38	5	23	16	9	15	4	35	11	27	33	22	17	37	3	32	19	20	28	29	26	10	7	8	18	40	21	31	2	6	12
375	0.7	1700	13	35	27	38	16	24	28	5	30	36	23	4	32	39	34	33	9	15	11	21	29	17	37	25	14	26	3	19	10	40	22	18	7	31	20	2	6	8	12
376	0.7	1800	39	14	27	9	15	24	13	28	32	25	35	40	11	30	21	36	38	5	34	4	23	37	33	3	17	29	16	26	22	19	20	2	6	10	18	31	12	7	8
377	0.7	1900	13	30	9	15	11	36	39	17	25	23	40	32	35	14	38	26	5	24	27	16	21	4	33	28	10	34	29	37	19	22	3	7	20	2	6	18	31	12	8
378	0.7	2000	13	30	14	38	25	16	23	24	5	39	35	17	9	15	27	40	11	21	4	32	26	28	10	22	20	36	7	34	3	8	33	37	19	2	18	29	31	6	12
379	0.7	2100	39	9	30	23	32	35	17	25	13	38	14	11	15	24	16	21	26	10	27	40	22	36	7	34	33	5	20	8	28	37	4	29	19	3	18	31	2	6	12
380	0.7	2200	13	9	27	25	5	4	16	30	35	28	24	17	33	14	11	15	23	29	40	39	21	32	22	20	38	36	34	3	37	19	26	10	2	6	7	8	18	12	31
381	0.7	2300	13	17	39	25	26	5	27	4	16	24	9	32	11	28	14	10	15	35	30	33	36	7	38	29	21	23	22	40	20	8	34	37	19	18	31	3	2	6	12
382	0.7	2400	39	25	5	30	27	9	15	16	17	38	35	22	33	20	13	24	28	29	40	23	4	32	11	26	21	14	10	36	7	34	3	8	37	19	2	6	18	31	12
383	0.7	2500	39	13	35	14	9	36	16	30	23	32	25	17	5	4	27	11	15	34	28	21	37	38	22	33	20	29	24	26	19	18	3	10	2	6	31	40	7	8	12

Table 7-42 Sequence, routings and cost estimates of remanufacturing function (30/44)

Test No.	Remanufacturing Method (1=Reuse, 2=Reincarnate, 3=Recycle, 4=Disposal)																																										Cost (£)
358	3	4	4	3	3	1	1	1	4	2	3	4	1	3	2	1	3	3	2	1	3	1	3	2	3	3	3	2	3	1	3	4	1	3	2	3	1	3	2	2	27,198
359	1	1	3	2	1	3	3	1	3	1	3	4	4	2	4	3	3	3	1	2	3	1	1	3	2	4	2	3	3	3	3	4	2	3	3	1	3	1	2	2	27,208
360	1	2	4	1	4	3	4	3	1	3	3	3	2	3	3	3	3	3	1	3	1	2	1	4	1	2	3	1	4	2	3	3	1	2	3	3	1	2	3	2	27,229
361	3	3	2	3	1	1	1	1	1	3	3	4	3	2	4	3	4	3	1	2	3	2	3	4	3	3	2	3	1	1	4	3	2	3	1	3	3	1	2	2	27,245
362	1	1	3	4	3	4	3	4	4	2	3	1	3	3	3	1	1	2	1	3	3	4	1	2	3	3	3	1	3	3	1	3	2	3	1	2	2	2	3	2	27,261
363	1	2	3	4	3	3	4	1	3	1	3	1	2	3	2	4	3	1	3	1	4	3	3	1	4	3	3	1	2	3	1	2	3	3	2	2	3	1	3	2	27,277
364	1	3	4	1	1	4	3	1	3	3	2	4	3	4	1	3	1	2	1	4	1	3	3	3	2	3	3	2	2	3	3	3	2	3	3	1	3	1	2	2	27,293
365	1	1	1	3	2	3	3	4	3	3	2	3	3	1	4	1	1	2	3	4	3	3	1	3	3	4	3	1	2	3	2	3	4	1	3	1	2	3	2	2	27,309
366	3	3	1	3	4	3	4	1	3	2	1	2	3	1	1	3	3	1	2	4	3	3	1	1	4	2	3	3	3	2	4	3	3	2	1	3	3	1	2	2	27,319
367	1	3	4	4	1	1	3	2	3	1	1	1	3	3	4	2	3	3	4	3	2	3	3	3	1	3	3	1	1	3	1	4	3	2	3	2	2	2	3	2	27,341
368	3	3	1	1	3	2	4	3	4	2	1	4	3	3	1	3	3	2	1	1	1	1	3	2	4	2	3	3	3	3	4	3	3	2	1	3	3	2	1	2	27,351
369	3	3	4	1	2	1	1	4	1	4	3	3	2	3	4	2	3	1	3	3	3	1	3	1	3	4	1	2	3	2	3	3	1	2	3	3	3	2	1	2	27,373
370	3	1	4	3	1	3	4	3	4	2	3	3	1	3	2	3	2	1	1	1	1	3	1	3	3	2	4	2	3	3	3	3	4	2	3	1	3	2	1	2	27,383
371	1	2	3	3	4	3	4	1	1	3	1	1	1	2	4	2	2	3	1	3	3	3	3	1	4	2	3	3	3	3	3	4	2	3	3	1	3	2	1	2	27,399
372	3	4	3	3	1	2	1	4	3	4	1	1	3	4	3	1	3	1	3	3	2	4	1	3	2	3	1	3	1	2	3	3	3	1	2	2	3	3	2	2	27,420
373	1	4	1	3	3	3	1	4	3	2	3	1	4	3	1	1	3	3	1	2	3	2	3	3	3	1	2	4	2	3	3	3	1	4	3	1	2	3	2	2	27,430
374	1	1	3	3	4	3	3	2	3	4	3	1	1	3	1	4	2	4	3	3	3	3	4	1	1	3	2	3	1	2	2	3	3	1	3	1	2	3	2	2	27,452
375	3	4	4	3	1	3	2	4	1	4	3	1	1	1	3	3	1	3	2	3	3	3	3	3	2	1	4	1	2	1	3	3	2	1	3	2	3	3	2	2	27,468
376	1	2	4	1	3	3	3	2	1	3	4	1	2	1	3	4	3	4	3	1	3	3	3	4	3	3	1	1	3	1	3	2	3	2	3	1	2	2	3	2	27,484
377	3	1	1	3	2	4	1	3	3	3	1	1	4	2	3	1	4	3	4	1	3	1	3	2	2	3	3	3	1	3	4	2	3	2	3	3	1	2	3	2	27,500
378	3	1	2	3	3	1	3	3	4	1	4	3	1	3	4	1	2	3	1	1	1	2	2	3	3	4	2	3	4	3	3	3	1	2	3	3	1	3	2	2	27,510
379	1	1	1	3	1	4	3	3	3	3	2	2	3	3	1	3	1	2	4	1	3	4	2	3	3	4	3	3	2	3	1	3	1	4	3	1	2	3	2	2	27,526
380	3	1	4	3	4	1	1	1	4	2	3	3	3	2	2	3	3	3	1	1	3	1	3	3	3	4	3	4	3	1	1	2	2	3	2	3	3	2	1	2	27,547
381	3	3	1	3	1	4	4	1	1	3	1	1	2	2	2	2	3	4	1	3	4	2	3	3	3	3	3	1	3	3	3	3	1	3	1	4	2	3	2	2	27,558
382	1	3	4	1	4	1	3	1	3	3	4	3	3	3	3	3	2	3	1	3	1	1	2	1	3	2	2	4	2	3	4	3	3	1	2	3	3	1	2	2	27,574
383	1	3	4	2	1	4	1	1	3	1	3	3	4	1	4	2	3	3	2	3	3	3	3	3	3	3	3	1	1	3	4	2	2	3	1	1	2	3	2	2	27,595

Table 7-43 Sequence, routings and cost estimates of remanufacturing function (31/44)

Test No.	Quality (q)	Distance (km)	Disassembly sequence (by Part Number)																																								
384	0.7	2600	13	14	9	15	11	24	32	25	35	17	39	5	38	26	16	10	30	21	36	7	23	22	27	28	4	20	33	8	40	29	34	3	37	19	18	31	2	6	12
385	0.7	2700	13	35	32	38	27	33	5	25	14	24	9	39	17	36	30	34	28	11	15	23	21	40	16	22	29	4	20	37	19	18	26	3	10	31	7	8	2	6	12
386	0.7	2800	39	13	25	17	24	38	9	15	5	27	16	11	28	22	40	33	14	26	20	35	30	23	10	4	29	21	36	7	32	8	34	37	3	2	19	6	18	31	12
387	0.7	2900	39	5	14	27	9	15	24	35	13	4	11	28	36	34	17	40	25	38	16	22	20	37	32	26	3	10	30	23	21	19	7	8	18	31	33	2	6	12	29
388	0.7	3000	39	36	5	30	25	13	27	32	38	23	9	15	16	28	11	24	35	40	4	17	22	34	21	14	33	26	3	10	29	7	8	37	20	19	18	2	6	31	12
389	0.7	3100	39	32	5	9	15	4	13	16	17	40	30	25	35	26	36	14	11	10	34	7	38	3	37	8	22	24	20	27	28	21	33	29	23	19	2	6	18	12	31
390	0.7	3200	13	27	30	24	25	14	35	28	32	23	38	39	9	15	33	11	17	26	29	21	40	16	10	36	7	34	5	22	4	8	37	20	3	2	19	18	6	12	31
391	0.7	3300	13	38	16	24	35	27	9	15	5	39	33	25	22	17	26	32	11	14	10	28	36	7	34	4	21	37	20	30	8	29	23	40	3	2	6	19	18	12	31
392	0.7	3400	39	32	27	33	25	38	17	35	14	13	26	9	11	30	23	28	24	10	15	5	40	4	21	16	29	36	7	22	20	34	37	8	19	18	31	3	2	6	12
393	0.7	3500	13	35	5	16	25	9	15	36	24	39	38	32	11	14	21	4	30	17	26	23	40	34	27	37	10	7	22	20	28	3	19	8	33	29	2	18	6	31	12
394	0.7	3600	39	13	5	32	38	17	35	24	4	9	15	27	33	28	11	30	16	22	21	20	14	29	40	36	34	25	23	3	26	2	37	6	10	7	19	18	31	8	12
395	0.7	3700	13	14	38	25	16	5	39	24	17	27	35	4	32	9	15	30	28	40	22	21	11	33	36	26	23	34	29	10	3	37	19	18	31	20	2	6	7	8	12
396	0.7	3800	13	27	38	36	30	28	17	5	35	34	9	15	32	4	33	23	3	29	25	11	21	16	22	14	20	2	6	24	39	40	26	37	19	18	10	31	12	7	8
397	0.7	3900	39	16	14	9	5	35	4	11	15	13	22	40	32	25	21	17	26	10	27	20	33	30	38	28	36	7	24	8	29	34	37	23	19	3	2	6	18	31	12
398	0.7	4000	13	17	35	38	39	14	32	16	9	15	25	30	27	28	21	40	26	23	22	20	33	24	5	11	4	10	29	36	7	34	8	3	2	37	6	19	18	12	31
399	0.7	4100	39	24	35	9	11	15	32	16	36	34	17	21	30	40	14	25	27	33	22	23	5	4	3	13	28	38	26	10	29	20	2	7	8	6	37	19	18	12	31
400	0.7	4200	13	9	15	38	14	27	39	33	30	17	28	40	23	36	5	11	29	25	4	35	16	21	26	22	10	32	20	34	24	37	3	2	6	7	19	18	8	12	31
401	0.7	4300	39	9	5	13	11	16	35	14	30	27	25	33	4	17	24	26	10	15	36	7	21	32	23	28	40	34	29	38	22	8	37	19	3	18	20	31	2	6	12
402	0.7	4400	39	32	9	15	24	35	38	40	30	21	11	14	27	33	28	16	22	23	17	13	25	20	26	29	10	36	7	8	5	4	34	3	37	2	6	19	18	12	31
403	0.7	4500	39	9	15	27	33	24	13	5	11	25	38	14	30	35	23	32	40	17	16	21	22	20	28	29	26	4	10	36	7	8	34	3	2	37	19	6	18	12	31
404	0.7	4600	13	9	15	38	36	35	34	25	37	32	17	5	4	30	27	40	23	3	21	16	33	22	26	14	28	20	2	39	11	6	10	29	24	19	7	8	18	31	12
405	0.7	4700	39	30	9	16	23	25	35	32	11	15	27	5	40	21	4	38	28	22	13	17	14	26	10	33	20	29	24	36	7	34	3	8	2	37	6	19	18	12	31
406	0.7	4800	13	5	24	14	30	4	25	38	17	26	16	9	15	11	40	39	32	35	21	10	23	36	7	34	37	8	19	3	27	28	33	29	22	20	2	6	18	12	31
407	0.7	4900	39	16	36	5	25	4	32	27	33	30	35	17	13	14	28	9	38	11	23	26	34	10	15	24	40	3	29	37	7	19	8	18	31	22	21	20	2	6	12
408	0.7	5000	13	17	14	36	9	32	30	25	27	28	5	35	23	26	24	16	38	34	33	11	15	37	19	39	18	31	4	21	29	10	7	8	22	3	40	20	2	6	12

Table 7-44 Sequence, routings and cost estimates of remanufacturing function (32/44)

Test No.	Remanufacturing Method (1=Reuse, 2=Reincarnate, 3=Recycle, 4=Disposal)																																										Cost (£)
384	3	2	1	3	2	3	1	3	4	3	1	4	3	1	1	2	1	3	4	2	3	3	4	2	1	3	3	3	1	3	3	4	3	1	3	1	2	3	2	2	27,605
385	3	4	1	3	4	3	4	3	2	3	1	1	3	4	1	3	2	2	3	3	3	1	1	3	3	1	3	3	1	3	1	4	2	1	2	3	2	3	2	2	27,627
386	1	3	3	3	3	3	1	3	4	4	1	2	2	3	1	3	2	1	3	4	1	3	2	1	3	3	4	2	1	3	3	3	4	2	1	3	3	1	2	2	27,637
387	1	4	2	4	1	3	3	4	3	1	2	2	4	3	3	1	3	3	1	3	3	3	1	1	4	2	1	3	3	1	2	3	3	1	3	2	3	2	3	2	27,659
388	1	4	4	1	3	3	4	1	3	3	1	3	1	2	2	3	4	1	1	3	3	3	3	2	3	1	4	2	3	2	3	3	3	1	3	2	3	1	2	2	27,675
389	1	1	4	1	3	1	3	1	3	1	1	3	4	1	4	2	2	2	3	2	3	4	3	3	3	3	3	4	2	3	3	3	3	1	2	3	3	2	1	2	27,691
390	3	4	1	3	3	2	4	2	1	3	3	1	1	3	3	2	3	1	3	3	1	1	2	4	2	3	4	3	1	3	3	3	4	2	1	3	3	2	1	2	27,701
391	3	3	1	3	4	4	1	3	4	1	3	3	3	3	1	1	2	2	2	2	4	2	3	1	3	3	3	1	3	3	3	1	4	2	3	1	3	2	1	2	27,717
392	1	1	4	3	3	3	3	4	2	3	1	1	2	1	3	2	3	2	3	4	1	1	3	1	3	4	2	3	3	3	3	3	1	3	1	4	2	3	2	2	27,733
393	3	4	4	1	3	1	3	4	3	1	3	1	2	2	3	1	1	3	1	3	1	3	4	3	2	2	3	3	2	4	1	3	3	3	2	3	3	1	2	2	27,754
394	1	3	4	1	3	3	4	3	1	1	3	4	3	2	2	1	1	3	3	3	2	3	1	4	3	3	3	4	1	2	3	3	2	2	1	3	1	3	2	2	27,770
395	3	2	3	3	1	4	1	3	3	4	4	1	1	1	3	1	2	1	3	3	2	3	4	1	3	3	3	2	4	3	1	3	1	3	2	3	2	3	2	2	27,786
396	3	4	3	4	1	2	3	4	4	3	1	3	1	1	3	3	4	3	3	2	3	1	3	2	3	2	3	3	1	1	1	3	1	3	2	1	2	2	3	2	27,802
397	1	1	2	1	4	4	1	2	3	3	3	1	1	3	3	3	1	2	4	3	3	1	3	2	4	2	3	3	3	3	3	3	1	4	2	3	3	1	2	2	27,812
398	3	3	4	3	1	2	1	1	1	3	3	1	4	2	3	1	1	3	3	3	3	3	4	2	1	2	3	4	2	3	3	4	2	3	3	1	3	2	1	2	27,828
399	1	3	4	1	2	3	1	1	4	3	3	3	1	1	2	3	4	3	3	3	4	1	4	3	2	3	1	2	3	3	2	2	3	3	3	1	3	2	1	2	27,850
400	3	1	3	3	2	4	1	3	1	3	2	1	3	4	4	2	3	3	1	4	1	3	1	3	2	1	3	3	3	3	4	2	3	2	1	3	3	2	1	2	27,865
401	1	1	4	3	2	1	4	2	1	4	3	3	1	3	3	1	2	3	4	2	3	1	3	2	1	3	3	3	3	3	3	1	4	3	3	1	2	3	2	2	27,876
402	1	1	1	3	3	4	3	1	1	3	2	2	4	3	2	1	3	3	3	3	3	3	1	3	2	4	2	3	4	1	3	4	3	2	3	1	3	2	1	2	27,892
403	1	1	3	4	3	3	3	4	2	3	3	2	1	4	3	1	1	3	1	3	3	3	2	3	1	1	2	4	2	3	3	4	2	3	1	3	3	2	1	2	27,907
404	3	1	3	3	4	4	3	3	3	1	3	4	1	1	4	1	3	4	3	1	3	3	1	2	2	3	2	1	2	3	2	3	3	1	2	3	3	1	2	2	27,929
405	1	1	1	1	3	3	4	1	2	3	4	4	1	3	1	3	2	3	3	3	2	1	2	3	3	3	3	4	2	3	4	3	2	3	3	1	3	2	1	2	27,939
406	3	4	3	2	1	1	3	3	3	1	1	1	3	2	1	1	1	4	3	2	3	4	2	3	3	3	1	4	4	2	3	3	3	3	2	3	3	2	1	2	27,955
407	1	1	4	4	3	1	1	4	3	1	4	3	3	2	2	1	3	2	3	1	3	2	3	3	1	4	3	3	2	1	3	3	1	3	3	3	2	3	2	2	27,977
408	3	3	2	4	1	1	1	3	4	2	4	4	3	1	3	1	3	3	3	2	3	3	1	1	3	1	1	3	3	2	2	3	3	4	1	3	2	3	2	2	27,993

Table 7-45 Sequence, routings and cost estimates of remanufacturing function (33/44)

Test No.	Quality (q)	Distance (km)	Disassembly sequence (by Part Number)																																											
409	0.8	0	39	9	5	24	25	11	17	30	23	38	35	4	14	27	28	32	33	13	26	29	10	15	16	21	36	7	34	40	3	22	37	20	2	6	19	8	18	31	12
410	0.8	100	39	32	36	25	14	16	17	34	35	27	30	5	13	9	15	38	21	22	4	23	28	37	11	33	20	3	2	6	26	24	29	40	10	7	19	8	18	12	31
411	0.8	200	39	5	9	15	30	16	25	14	17	24	23	27	40	33	22	35	38	36	13	34	26	21	4	3	11	20	2	28	6	37	29	32	19	10	18	12	7	31	8
412	0.8	300	13	39	25	9	15	17	27	28	5	35	24	33	38	4	26	14	36	11	16	40	22	20	30	34	10	29	7	3	21	37	8	2	6	23	19	32	18	12	31
413	0.8	400	13	38	27	36	30	9	39	25	28	32	11	34	5	24	23	33	17	14	29	4	3	26	37	10	15	19	7	8	16	22	40	35	18	20	31	21	2	6	12
414	0.8	500	39	9	16	38	27	32	30	23	5	14	4	35	28	11	15	33	17	13	24	40	21	29	25	26	22	10	36	7	34	20	37	8	19	3	2	18	6	12	31
415	0.8	600	39	38	17	5	13	4	14	9	15	27	16	36	22	24	28	34	32	3	35	11	33	37	20	30	29	25	26	40	10	23	7	19	21	2	8	6	18	12	31
416	0.8	700	39	9	15	5	4	38	35	30	25	13	16	24	14	36	32	27	23	21	33	34	3	40	17	22	11	28	26	10	37	19	7	18	20	31	2	29	6	12	8
417	0.8	800	39	5	25	9	38	32	17	16	27	13	33	35	11	15	30	14	40	23	22	26	4	36	28	24	34	3	21	20	10	29	7	37	19	18	2	6	8	12	31
418	0.8	900	39	38	5	27	13	16	32	36	33	28	17	35	4	9	15	34	30	40	11	22	14	3	23	21	24	29	25	20	2	37	19	26	18	6	10	7	12	31	8
419	0.8	1000	39	38	32	35	25	30	23	14	13	9	15	5	4	21	24	17	40	11	27	26	10	33	28	16	22	20	36	7	34	37	8	3	29	19	2	6	18	31	12
420	0.8	1100	39	9	15	35	24	40	17	13	32	21	14	25	16	5	22	38	11	36	30	27	20	34	4	37	28	23	3	33	26	10	19	2	6	7	18	29	31	12	8
421	0.8	1200	39	9	11	15	13	40	38	32	27	24	25	30	17	26	16	23	22	28	35	33	21	5	29	36	20	4	14	10	7	34	3	37	19	8	2	6	18	31	12
422	0.8	1300	13	30	17	38	32	27	5	33	4	39	25	36	14	26	16	24	35	9	11	15	28	29	34	3	22	21	23	20	40	10	37	2	19	7	8	6	18	12	31
423	0.8	1400	13	14	27	39	38	25	17	33	9	15	30	24	5	26	40	23	35	28	29	4	11	32	10	21	16	36	7	22	20	34	3	8	37	2	19	6	18	31	12
424	0.8	1500	13	17	30	39	35	9	15	5	24	14	38	11	32	27	25	28	26	40	16	33	23	22	21	4	20	29	10	36	7	34	37	19	8	3	2	6	18	31	12
425	0.8	1600	39	14	17	5	4	25	16	38	32	9	15	35	30	40	23	11	21	27	28	22	33	24	13	26	10	36	7	34	37	29	3	19	20	18	8	31	2	6	12
426	0.8	1700	13	16	14	5	25	24	27	28	4	33	17	9	32	39	36	11	15	38	26	30	29	34	3	40	22	37	35	20	23	10	7	21	19	18	8	31	2	6	12
427	0.8	1800	39	17	27	14	9	24	35	32	36	30	13	16	33	28	34	5	4	37	11	38	23	25	29	3	26	19	18	10	15	31	21	7	22	40	20	2	6	12	8
428	0.8	1900	13	14	9	32	24	35	38	5	25	4	27	33	17	39	11	15	28	16	40	26	10	21	36	7	8	30	22	29	34	37	23	20	19	18	3	31	2	6	12
429	0.8	2000	39	13	16	35	30	27	32	36	28	38	9	15	24	23	21	5	33	14	29	34	4	3	37	11	17	25	22	19	40	20	18	31	2	26	6	10	12	7	8
430	0.8	2100	39	27	36	34	30	38	35	23	25	37	14	5	28	4	32	9	15	13	21	40	16	33	29	24	11	3	22	19	17	20	18	2	26	31	6	12	10	7	8
431	0.8	2200	39	16	9	17	24	30	11	15	25	32	5	27	28	38	4	35	22	40	14	33	13	23	26	20	10	29	36	34	21	3	37	7	19	18	31	8	2	6	12
432	0.8	2300	13	30	16	36	35	39	24	5	9	15	11	25	22	23	34	37	4	21	32	3	27	33	28	17	26	20	14	40	19	38	2	29	10	7	18	31	8	6	12
433	0.8	2400	39	13	25	16	38	9	24	11	15	36	35	27	17	22	26	20	33	40	21	32	5	34	14	28	4	37	3	2	10	30	23	29	6	7	8	19	18	31	12
434	0.8	2500	13	17	24	9	16	30	27	5	38	33	25	11	23	26	14	28	29	4	10	15	22	35	20	36	7	8	40	32	39	21	34	3	37	2	6	19	18	31	12

Table 7-46 Sequence, routings and cost estimates of remanufacturing function (34/44)

Test No.	Remanufacturing Method (1=Reuse, 2=Reincarnate, 3=Recycle, 4=Disposal)																																										Cost (£)
409	1	1	4	3	3	2	3	1	3	3	4	1	2	4	2	1	3	3	1	3	2	3	1	3	4	2	3	1	4	3	3	3	2	3	1	3	3	1	2	2	26,102
410	1	1	4	3	2	1	3	3	4	4	1	4	3	1	3	3	3	3	1	3	2	3	2	3	3	4	2	3	1	3	3	1	2	2	1	3	3	2	1	2	26,123
411	1	4	1	3	1	1	3	2	3	3	3	4	1	3	3	4	3	4	3	3	1	3	1	4	2	3	2	2	3	3	3	1	1	2	3	2	2	1	3	2	26,139
412	3	1	3	1	3	3	4	2	4	4	3	3	3	1	1	2	4	2	1	1	3	3	1	3	2	3	2	4	3	3	3	2	3	3	1	1	3	2	1	2	26,155
413	3	3	4	4	1	1	1	3	2	1	2	3	4	3	3	3	3	2	3	1	4	1	3	2	3	1	2	3	1	3	1	4	3	3	1	3	2	3	2	2	26,170
414	1	1	1	3	4	1	1	3	4	2	1	4	2	2	3	3	3	3	3	1	3	3	3	1	3	2	4	2	3	3	3	3	1	4	2	3	3	2	1	2	26,181
415	1	3	3	4	3	1	2	1	3	4	1	4	3	3	2	3	1	4	4	2	3	3	3	1	3	3	1	1	2	3	2	1	3	2	3	3	3	2	1	2	26,202
416	1	1	3	4	1	3	4	1	3	3	1	3	2	4	1	4	3	3	3	3	4	1	3	3	2	2	1	2	3	1	2	3	3	1	2	3	3	2	3	2	26,218
417	1	4	3	1	3	1	3	1	4	3	3	4	2	3	1	2	1	3	3	1	1	4	2	3	3	4	3	3	2	3	2	3	1	3	2	3	3	2	1	2	26,234
418	1	3	4	4	3	1	1	4	3	2	3	4	1	1	3	3	1	1	2	3	2	4	3	3	3	3	3	3	2	3	1	1	3	3	2	2	2	1	3	2	26,250
419	1	3	1	4	3	1	3	2	3	1	3	4	1	3	3	3	1	2	4	1	2	3	2	1	3	3	4	2	3	3	3	4	3	1	2	3	3	1	2	2	26,261
420	1	1	3	4	3	1	3	3	1	3	2	3	1	4	3	3	2	4	1	4	3	3	1	3	2	3	4	3	1	2	1	2	3	2	3	3	1	2	3	2	26,282
421	1	1	2	3	3	1	3	1	4	3	3	1	3	1	1	3	3	2	4	3	3	4	3	4	3	1	2	2	2	3	4	3	1	3	2	3	3	1	2	2	26,298
422	3	1	3	3	1	4	4	3	1	1	3	4	2	1	1	3	4	1	2	3	2	3	3	4	3	3	3	3	1	2	3	2	1	2	3	3	3	2	1	2	26,314
423	3	2	4	1	3	3	3	3	1	3	1	3	4	1	1	3	4	2	3	1	2	1	2	3	1	4	2	3	3	3	4	3	3	2	1	3	3	1	2	2	26,324
424	3	3	1	1	4	1	3	4	3	2	3	2	1	4	3	2	1	1	1	3	3	3	3	1	3	3	2	4	2	3	3	1	3	4	2	3	3	1	2	2	26,340
425	1	2	3	4	1	3	1	3	1	1	3	4	1	1	3	2	3	4	2	3	3	3	3	1	2	4	2	3	3	3	4	1	3	3	3	1	2	3	2	2	26,356
426	3	1	2	4	3	3	4	2	1	3	3	1	1	1	4	2	3	3	1	1	3	3	4	1	3	3	4	3	3	2	2	3	1	3	3	1	2	3	2	2	26,377
427	1	3	4	2	1	3	4	1	4	1	3	1	3	2	3	4	1	3	2	3	3	3	3	4	1	1	3	2	3	1	3	2	3	1	3	2	3	2	3	2	26,393
428	3	2	1	1	3	4	3	4	3	1	4	3	3	1	2	3	2	1	1	1	2	3	4	2	3	1	3	3	3	3	3	3	1	3	4	1	2	3	2	2	26,404
429	1	3	1	4	1	4	1	4	2	3	1	3	3	3	3	4	3	2	3	3	1	4	3	2	3	3	3	1	1	3	3	1	2	1	3	2	2	2	3	2	26,425
430	1	4	4	3	1	3	4	3	3	3	2	4	2	1	1	1	3	3	3	1	1	3	3	3	2	4	3	1	3	3	3	2	1	1	3	2	2	2	3	2	26,441
431	1	1	1	3	3	1	2	3	3	1	4	4	2	3	1	4	3	1	2	3	3	3	1	3	2	3	4	3	3	4	3	2	1	3	1	3	2	3	2	2	26,457
432	3	1	1	4	4	1	3	4	1	3	2	3	3	3	3	3	1	3	1	4	4	3	2	3	1	3	2	1	1	3	2	3	2	2	3	1	3	3	2	2	26,473
433	1	3	3	1	3	1	3	2	3	4	4	4	3	3	1	3	3	1	3	1	4	3	2	2	1	3	4	2	2	1	3	3	3	2	3	1	3	1	2	2	26,488
434	3	3	3	1	1	1	4	4	3	3	3	2	3	1	2	2	3	1	2	3	3	4	3	4	2	3	1	1	1	3	3	4	3	2	3	1	3	1	2	2	26,499

Table 7-47 Sequence, routings and cost estimates of remanufacturing function (35/44)

| Test No. | Quality (q) | Distance (km) | Disassembly sequence (by Part Number) | | |

Table 7-48 Sequence, routings and cost estimates of remanufacturing function (36/44)

Test No.	Remanufacturing Method (1=Reuse, 2=Reincarnate, 3=Recycle, 4=Disposal)																																											Cost (£)
435	1	3	1	3	3	3	1	1	2	1	4	4	3	3	3	4	2	1	1	1	3	2	3	3	4	2	3	2	3	4	3	1	3	3	2	3	3	1	2	2	26,520
436	3	4	1	3	2	1	3	2	2	4	1	4	3	3	3	3	1	3	1	3	1	3	3	4	1	1	4	3	3	3	1	1	2	2	3	3	2	3	2	2	26,536
437	1	1	1	3	3	3	4	3	3	2	3	1	2	4	3	1	1	3	1	3	4	3	3	2	2	1	4	2	3	3	4	2	3	3	3	1	3	1	2	2	26,547
438	3	1	3	1	3	3	2	3	1	4	1	4	1	4	1	1	2	3	2	4	2	3	1	3	3	2	3	3	3	3	1	3	3	4	1	3	2	3	2	2	26,563
439	1	1	1	3	3	2	2	4	4	3	1	3	1	2	3	4	2	3	3	3	1	3	3	4	3	3	1	1	4	2	3	2	3	3	1	3	1	3	2	2	26,579
440	3	3	1	1	4	1	4	1	2	3	4	1	3	3	3	1	2	3	3	1	3	3	2	3	3	1	4	2	3	4	3	1	2	3	2	3	3	2	1	2	26,600
441	1	4	3	2	4	1	4	3	3	3	1	1	1	4	3	1	4	2	3	3	3	2	3	1	1	3	3	3	1	2	1	3	3	3	2	2	3	3	2	2	26,616
442	1	1	3	4	1	1	3	3	2	4	3	1	2	4	3	3	2	3	1	3	4	3	1	3	3	1	2	4	3	2	3	3	3	1	2	3	3	1	2	2	26,632
443	3	3	1	3	4	4	3	1	3	3	2	1	3	1	1	4	3	2	1	1	3	3	3	1	2	4	2	3	4	3	1	2	3	2	3	3	1	3	2	2	26,642
444	3	1	3	1	3	1	4	1	1	3	2	3	4	3	1	4	2	1	3	3	3	2	1	2	4	2	3	3	3	3	3	4	2	1	3	3	3	1	2	2	26,658
445	3	1	3	4	1	3	3	1	4	1	2	4	1	1	1	3	2	3	4	2	2	3	3	1	3	3	3	4	3	2	3	2	3	3	3	1	3	1	2	2	26,679
446	1	3	2	3	3	1	4	3	3	1	1	2	3	3	2	4	3	3	1	4	4	1	1	3	2	1	3	2	3	3	3	4	2	3	1	3	3	1	2	2	26,695
447	3	4	1	3	3	2	1	1	3	4	1	3	4	2	4	3	1	3	3	2	1	3	3	3	3	3	1	1	3	1	2	3	4	2	3	2	3	1	2	2	26,711
448	3	1	4	3	2	1	2	1	4	1	4	3	3	2	3	3	4	3	3	1	1	2	3	3	3	1	2	1	3	4	3	1	3	3	1	3	2	3	2	2	26,727
449	3	3	1	3	1	4	2	3	3	1	1	4	2	2	1	1	1	3	4	1	3	3	3	3	4	3	3	3	3	4	2	1	2	3	2	3	3	1	2	2	26,743
450	3	1	3	4	2	1	1	3	3	3	1	2	3	1	4	1	2	1	1	3	3	2	3	3	4	2	3	4	3	3	4	3	1	3	2	3	3	2	1	2	26,754
451	3	1	3	1	4	3	4	1	3	4	4	2	1	3	3	2	3	3	1	1	3	1	3	3	1	3	3	3	1	1	4	2	2	2	3	2	3	3	2	2	26,775
452	1	4	4	3	1	1	3	3	1	4	4	1	2	3	3	3	2	3	2	3	1	3	3	1	2	3	1	3	3	1	2	3	1	4	3	3	2	3	2	2	26,791
453	3	1	2	1	1	3	3	4	4	1	2	3	3	3	3	1	3	4	4	1	3	2	3	1	4	3	2	3	2	3	2	3	3	3	1	3	1	2	1	2	26,806
454	3	4	3	1	4	3	3	1	1	1	3	3	3	1	3	2	4	1	3	3	3	1	4	4	3	3	2	1	2	2	3	2	3	2	3	1	3	2	1	2	26,822
455	3	4	1	3	3	4	3	1	3	1	2	3	3	2	1	4	1	1	2	4	2	1	3	3	1	3	3	4	2	3	1	3	3	1	3	2	3	3	2	2	26,833
456	3	3	1	2	1	4	1	3	1	4	4	4	3	3	1	2	4	1	2	1	3	3	3	3	3	1	1	2	3	3	3	2	3	3	3	1	2	3	2	2	26,854
457	1	4	1	1	3	3	3	3	2	4	1	2	3	3	1	4	2	3	1	1	2	1	4	2	3	3	3	3	4	3	2	3	3	3	3	1	3	2	1	2	26,865
458	1	3	4	3	2	1	1	1	3	1	3	3	1	4	4	1	3	2	1	2	3	3	2	3	4	2	3	3	3	3	3	1	3	4	3	1	2	3	2	2	26,881
459	1	4	3	1	1	3	2	4	1	3	4	3	3	1	2	1	3	3	1	2	2	3	4	2	3	3	3	4	1	3	3	3	3	2	1	3	3	1	2	2	26,897

Table 7-49 Sequence, routings and cost estimates of remanufacturing function (37/44)

Test No.	Quality (q)	Distance (km)	Disassembly sequence (by Part Number)																																										
460	0.9	0	13	24	30	9	39	23	17	38	16	25	35	36	32	11	15	26	5	4	27	28	33	14	29	34	22	20	10	21	40	7	8	3	2	6	37	19	18	31	12
461	0.9	100	39	30	13	9	15	11	27	35	25	16	32	5	4	28	23	33	24	29	14	38	17	26	10	21	40	22	36	7	20	34	3	8	2	6	37	19	18	12	31
462	0.9	200	13	9	32	17	16	36	11	15	35	39	21	34	37	40	22	25	26	24	5	30	27	14	10	33	23	4	3	19	18	7	38	8	28	31	20	2	6	29	12
463	0.9	300	39	9	15	13	14	30	25	38	40	23	27	33	28	5	17	11	32	35	36	16	34	26	10	29	24	4	37	7	21	22	20	8	19	18	31	3	2	6	12
464	0.9	400	13	38	27	33	28	32	9	39	17	25	11	15	26	40	36	5	14	30	24	23	29	4	34	3	37	10	7	16	19	8	18	35	21	31	22	20	2	6	12
465	0.9	500	39	25	32	30	23	27	16	28	36	9	11	15	22	35	40	21	17	33	24	20	13	26	29	38	5	34	37	4	14	3	2	19	6	18	31	12	10	7	8
466	0.9	600	13	39	17	9	15	30	25	24	16	11	26	23	35	21	40	27	32	28	38	14	10	33	36	7	22	29	34	20	5	37	8	4	3	19	18	2	6	31	12
467	0.9	700	13	14	25	9	39	17	35	38	11	27	33	24	16	30	5	28	32	26	10	15	4	36	7	22	8	21	29	20	40	34	3	37	2	6	23	19	18	31	12
468	0.9	800	39	32	25	27	13	30	33	5	9	15	14	11	17	35	40	24	28	21	26	38	16	22	36	34	4	37	29	20	10	7	8	3	23	19	2	18	6	12	31
469	0.9	900	39	16	13	25	17	35	5	38	30	24	9	15	22	4	23	11	14	26	10	36	7	21	32	34	27	3	40	37	20	28	19	8	33	18	31	29	2	6	12
470	0.9	1000	39	35	30	14	9	15	5	13	40	11	25	36	4	38	16	34	3	32	21	27	17	23	28	37	26	24	19	22	33	10	7	29	18	20	31	2	6	8	12
471	0.9	1100	39	25	14	30	35	16	27	38	9	15	33	22	23	24	21	28	5	11	17	13	20	29	26	32	40	10	4	36	7	34	8	3	2	37	6	19	18	12	31
472	0.9	1200	39	27	24	9	15	28	25	13	17	38	14	11	35	5	30	32	33	4	29	16	40	22	26	10	36	7	8	20	21	34	3	37	23	2	6	19	18	12	31
473	0.9	1300	39	27	24	9	13	25	30	36	32	11	15	17	35	5	34	40	33	4	26	3	28	14	38	16	23	37	22	19	21	10	7	18	20	29	2	6	12	31	8
474	0.9	1400	39	14	16	9	32	25	5	35	24	11	15	27	21	22	17	13	4	30	28	40	23	38	26	10	36	7	33	29	34	20	8	3	37	19	2	6	18	12	31
475	0.9	1500	39	14	16	32	17	24	13	27	5	30	25	28	4	33	38	9	15	22	26	35	23	29	20	40	11	10	21	36	7	34	8	3	2	6	37	19	18	31	12
476	0.9	1600	13	25	17	27	30	26	9	38	14	23	33	28	39	24	16	29	32	11	5	35	10	15	4	36	7	21	8	34	40	22	20	3	2	37	19	18	31	6	12
477	0.9	1700	13	14	38	17	30	25	5	16	24	9	15	23	11	26	40	4	22	35	10	27	21	36	7	33	28	32	34	37	29	3	20	19	8	18	2	39	6	12	31
478	0.9	1800	13	16	17	35	14	9	15	22	20	40	25	39	11	24	21	32	26	38	30	5	27	10	4	33	36	7	34	3	2	28	29	8	37	23	19	18	31	6	12
479	0.9	1900	39	38	27	14	28	36	16	17	9	15	34	37	25	30	24	13	32	35	40	22	33	20	21	29	23	19	5	26	11	4	18	10	3	2	7	31	8	6	12
480	0.9	2000	13	17	14	25	9	15	11	32	38	5	30	16	35	24	21	22	39	27	26	10	40	33	20	23	36	7	4	8	28	34	29	37	3	19	2	6	18	31	12
481	0.9	2100	39	24	13	17	16	5	30	25	32	9	15	26	23	22	40	14	38	27	33	28	35	29	11	10	21	4	36	7	20	8	34	37	19	3	2	18	6	12	31
482	0.9	2200	39	14	35	5	13	17	16	32	30	24	38	25	9	26	4	11	10	15	23	40	21	27	36	7	34	8	28	22	37	33	29	3	20	19	18	2	6	12	31
483	0.9	2300	13	5	16	9	15	11	27	17	32	38	22	14	35	21	24	25	20	26	28	40	4	39	33	10	36	7	34	3	37	8	2	6	30	29	23	19	18	12	31
484	0.9	2400	39	35	32	24	16	9	11	15	13	30	17	23	25	22	26	21	20	5	38	14	4	10	36	7	34	40	27	33	8	3	2	6	37	28	19	18	31	29	12
485	0.9	2500	13	9	15	24	36	16	22	30	39	25	17	35	23	21	26	14	11	32	27	40	5	28	20	10	33	38	4	7	29	34	37	19	3	2	6	8	18	31	12

Table 7-50 Sequence, routings and cost estimates of remanufacturing function (38/44)

Test No.	Remanufacturing Method (1=Reuse, 2=Reincarnate, 3=Recycle, 4=Disposal)																																									Cost (£)
460	3	3	1	1	1	3	3	3	1	3	4	4	1	2	3	1	4	1	4	2	3	2	3	3	3	3	2	3	1	2	3	4	2	3	3	1	3	1	2	2	25,016
461	1	1	3	1	3	2	4	4	3	1	1	4	1	2	3	3	3	3	2	3	3	1	2	3	1	3	4	2	3	3	4	3	2	3	3	1	3	2	1	2	25,011
462	3	1	1	3	1	4	2	3	4	1	3	3	3	1	3	3	1	3	4	1	4	2	2	3	3	1	4	1	3	2	3	3	2	1	3	2	3	3	2	2	25,032
463	1	1	3	3	2	1	3	3	1	3	4	3	2	4	3	2	1	4	4	1	3	1	2	3	3	1	3	2	3	3	3	3	1	3	1	4	2	3	2	2	25,048
464	3	3	4	3	2	1	1	1	3	3	2	3	1	1	4	4	2	1	3	3	3	1	3	4	3	2	2	1	1	3	3	4	3	1	3	3	2	3	2	2	25,064
465	1	3	1	1	3	4	1	2	4	1	2	3	3	4	1	3	3	3	3	3	3	1	3	3	4	3	3	1	2	4	2	1	3	3	1	2	2	2	3	2	25,080
466	3	1	3	1	3	1	3	3	1	2	1	3	4	3	1	4	1	2	3	2	2	3	4	2	3	3	3	3	4	3	3	1	4	1	3	2	3	1	2	2	25,091
467	3	2	3	1	1	3	4	3	2	4	3	3	1	1	4	2	1	1	2	3	1	4	2	3	3	3	3	3	1	3	4	3	2	3	3	1	3	1	2	2	25,107
468	1	1	3	4	3	1	3	4	1	3	2	2	3	4	1	3	2	3	1	3	1	3	4	3	1	3	3	3	2	2	3	4	3	1	2	3	3	2	1	2	25,127
469	1	1	3	3	3	4	4	3	1	3	1	3	3	1	3	2	2	1	2	4	2	3	1	3	4	4	1	3	3	2	1	3	3	3	1	3	2	3	2	2	25,139
470	1	4	1	2	1	3	4	3	1	2	3	4	1	3	1	3	4	1	3	4	3	3	2	3	1	3	1	3	3	2	2	3	3	3	1	2	3	3	2	2	25,159
471	1	3	2	1	4	1	4	3	1	3	3	3	3	3	3	2	4	2	3	3	3	3	1	1	1	2	1	4	2	3	3	4	2	3	3	1	3	2	1	2	25,170
472	1	4	3	1	3	2	3	3	3	3	2	2	4	4	1	1	3	1	3	1	1	3	1	2	4	2	3	3	3	3	4	3	3	2	3	1	3	2	1	2	25,186
473	1	4	3	1	3	3	1	4	1	2	3	3	4	4	3	1	3	1	1	4	2	2	3	1	3	3	3	1	3	2	2	3	3	3	2	3	2	1	3	2	25,207
474	1	2	1	1	1	3	4	4	3	2	3	4	3	3	3	3	1	1	2	1	3	3	1	2	4	2	3	3	3	3	3	4	3	1	2	3	3	2	1	2	25,218
475	1	2	1	1	3	3	3	4	4	1	3	2	1	3	3	1	3	3	1	4	3	3	3	1	2	2	3	4	2	3	3	4	2	3	3	1	3	1	2	2	25,234
476	3	3	3	4	1	1	1	3	2	3	3	2	1	3	1	3	1	2	4	4	2	3	1	4	2	3	3	3	1	3	3	4	2	3	1	3	1	3	2	2	25,250
477	3	2	3	3	1	3	4	1	3	1	3	3	2	1	1	1	3	4	2	4	3	4	2	3	2	1	3	3	3	4	3	1	3	3	2	1	3	2	1	2	25,266
478	3	1	3	4	2	1	3	3	3	1	3	1	2	3	3	1	1	3	1	4	4	2	1	3	4	2	3	4	2	2	3	3	3	3	1	3	1	3	2	2	25,298
479	1	3	4	2	2	4	1	3	1	3	3	3	3	1	3	3	1	4	1	3	3	3	3	3	3	1	4	1	2	1	3	2	4	2	2	1	3	3	2	2	25,318
480	3	3	2	3	1	3	2	1	3	4	1	1	4	3	3	3	1	4	1	2	1	3	3	3	4	2	1	3	2	3	3	3	4	1	2	3	3	1	2	2	25,329
481	1	3	3	3	1	4	1	3	1	1	3	1	3	3	1	2	3	4	3	2	4	3	2	2	3	1	4	2	3	3	3	3	1	4	2	3	3	2	1	2	25,345
482	1	2	4	4	3	3	1	1	1	3	3	3	1	1	1	2	2	3	3	1	3	4	4	2	3	3	2	3	3	3	3	4	3	1	3	2	3	2	1	2	25,361
483	3	4	1	1	3	2	4	3	1	3	3	2	4	3	3	3	3	1	2	1	1	1	3	2	4	2	3	4	3	3	2	3	1	3	3	1	3	2	1	2	25,377
484	1	4	1	3	1	1	2	3	3	1	3	3	3	3	1	3	3	4	3	2	1	2	4	2	3	1	4	3	3	4	2	3	3	2	1	3	1	3	2	2	25,393
485	3	1	3	3	4	1	3	1	1	3	3	4	3	3	1	2	2	1	4	1	4	2	3	2	3	3	1	2	3	3	3	1	4	2	3	3	3	1	2	2	25,414

Table 7-51 Sequence, routings and cost estimates of remanufacturing function (39/44)

Test No.	Quality (q)	Distance (km)	Disassembly sequence (by Part Number)																																											
486	0.9	2600	39	30	5	16	27	9	15	38	22	13	24	25	17	33	23	36	28	4	35	34	20	29	26	37	40	11	3	14	10	19	32	7	8	18	21	2	6	31	12
487	0.9	2700	39	5	32	30	9	15	17	13	16	23	24	27	36	35	25	22	21	11	33	38	40	28	14	4	20	34	26	29	37	10	19	7	18	3	8	31	2	6	12
488	0.9	2800	13	14	25	24	17	30	32	9	15	26	27	39	40	38	28	16	11	22	5	10	35	20	33	23	29	4	21	36	7	34	8	3	37	19	18	2	6	12	31
489	0.9	2900	39	9	25	27	24	38	17	28	5	32	30	23	4	33	14	36	34	16	11	15	35	40	13	26	3	21	29	10	37	19	22	7	20	18	2	31	6	8	12
490	0.9	3000	13	35	27	5	33	24	4	25	38	9	17	39	11	15	30	28	14	32	21	40	26	36	10	16	22	20	34	23	3	29	2	6	7	8	37	19	18	12	31
491	0.9	3100	13	24	9	15	27	33	30	40	5	39	23	11	4	35	16	22	32	28	14	17	29	21	20	25	26	10	36	7	38	34	3	2	8	37	19	6	18	12	31
492	0.9	3200	13	9	32	14	39	35	11	15	38	40	36	17	24	25	26	34	16	22	30	37	21	23	19	5	18	31	20	10	7	8	4	27	3	28	33	29	2	6	12
493	0.9	3300	13	17	39	35	38	30	23	5	16	25	24	9	15	11	26	32	22	14	21	4	10	36	7	27	8	34	37	20	19	33	18	40	31	3	2	28	6	12	29
494	0.9	3400	39	27	30	28	14	23	35	17	36	33	34	5	29	24	37	38	9	15	32	4	13	16	11	25	21	40	26	3	22	19	18	31	10	20	7	2	8	6	12
495	0.9	3500	39	25	35	27	17	9	15	32	40	21	36	5	33	30	11	14	13	28	26	23	16	24	22	10	20	4	34	38	29	3	7	37	8	2	19	18	31	6	12
496	0.9	3600	39	32	16	27	17	9	38	24	5	4	13	25	26	33	28	11	35	14	30	23	29	10	15	36	7	8	22	40	20	21	34	3	2	6	37	19	18	12	31
497	0.9	3700	13	36	32	39	30	9	15	24	25	17	40	34	27	14	16	35	22	21	5	33	37	4	3	26	11	23	20	38	19	10	2	7	8	6	18	28	31	29	12
498	0.9	3800	39	38	27	9	15	32	28	33	17	25	14	24	16	5	13	30	11	4	29	35	23	21	40	26	22	20	10	36	7	8	34	3	37	2	19	18	31	6	12
499	0.9	3900	39	16	24	32	13	9	5	4	38	14	17	27	30	35	11	15	22	20	33	28	21	25	26	40	23	10	29	36	7	8	34	3	37	2	6	19	18	31	12
500	0.9	4000	39	24	38	17	27	9	15	14	33	11	5	40	35	13	28	25	30	16	21	32	4	26	10	22	36	7	23	8	20	34	37	3	19	29	18	2	6	12	31
501	0.9	4100	39	27	28	25	16	32	5	13	24	9	15	14	38	11	30	35	17	26	4	10	33	23	36	7	29	34	8	3	37	19	18	22	21	40	31	20	2	6	12
502	0.9	4200	13	16	27	17	30	25	38	9	15	35	39	5	24	40	4	33	22	26	21	20	36	34	28	23	14	3	2	32	11	29	10	37	19	6	7	18	8	12	31
503	0.9	4300	13	38	30	32	23	25	9	15	11	40	39	17	36	35	21	24	34	16	26	37	27	14	5	28	10	19	22	7	4	18	20	31	8	33	29	3	2	6	12
504	0.9	4400	39	13	9	15	5	27	33	17	24	40	4	35	16	22	14	11	38	25	26	20	32	30	21	28	10	29	36	7	34	8	37	3	2	6	23	19	18	31	12
505	0.9	4500	39	35	13	16	25	38	24	17	36	32	34	26	30	9	15	22	14	5	21	11	40	23	37	27	19	20	33	28	29	18	4	3	10	7	8	2	6	12	31
506	0.9	4600	13	38	25	30	32	27	17	36	9	15	34	23	24	37	5	16	35	22	33	39	21	4	3	14	40	20	19	2	6	28	11	26	10	18	31	7	29	12	8
507	0.9	4700	13	38	5	27	33	32	25	9	15	30	11	28	17	14	35	23	24	21	4	26	16	10	40	36	7	29	22	8	34	20	37	19	3	18	2	6	39	12	31
508	0.9	4800	13	5	36	39	30	17	23	27	34	37	16	9	38	4	32	11	33	25	3	28	35	29	26	24	14	10	15	22	19	21	7	18	40	8	31	20	2	6	12
509	0.9	4900	39	38	25	9	27	36	32	14	13	11	15	35	40	30	23	16	28	5	4	21	24	22	33	29	17	34	3	20	37	2	19	18	31	6	12	26	10	7	8
510	0.9	5000	13	35	32	38	25	9	15	24	30	5	14	21	39	40	11	36	4	17	34	16	3	26	27	23	33	28	10	7	8	37	22	20	2	6	29	19	18	12	31

Table 7-52 Sequence, routings and cost estimates of remanufacturing function (40/44)

Test No.	Remanufacturing Method (1=Reuse, 2=Reincarnate, 3=Recycle, 4=Disposal)																																											Cost (£)
486	1	1	4	1	4	1	3	3	3	3	3	3	3	3	3	4	2	1	4	3	3	3	1	3	1	2	4	2	2	1	1	2	3	3	3	2	3	1	2	2	25,429
487	1	4	1	1	1	3	3	3	1	3	3	4	4	4	3	3	3	2	3	3	1	2	2	1	3	3	1	3	3	2	1	2	3	4	3	1	2	3	2	2	25,445
488	3	2	3	3	3	1	1	1	3	1	4	1	1	3	2	1	2	3	4	2	4	3	3	3	3	1	3	4	2	3	3	4	3	1	3	2	3	2	1	2	25,457
489	1	1	3	4	3	3	3	2	4	1	1	3	1	3	2	4	3	1	2	3	4	1	3	1	4	3	3	2	3	1	3	2	3	3	2	1	3	3	2	2	25,477
490	3	4	4	4	3	3	1	3	3	1	3	1	2	3	1	2	2	1	3	1	1	4	2	1	3	3	3	3	4	3	2	3	2	3	3	1	3	2	1	2	25,493
491	3	3	1	3	4	3	1	1	4	1	3	2	1	4	1	3	1	2	2	3	3	3	3	3	1	2	4	2	3	3	4	2	3	3	1	3	3	2	1	2	25,504
492	3	1	1	2	1	4	2	3	3	1	4	3	3	3	1	3	1	3	1	3	3	3	1	4	3	1	3	2	2	3	1	4	4	2	3	3	2	3	2	2	25,525
493	3	3	1	4	3	1	3	4	1	3	3	1	3	2	1	1	3	2	3	1	2	4	2	4	3	3	3	3	1	3	3	1	1	4	2	2	3	2	3	2	25,536
494	1	4	1	2	2	3	4	3	4	3	3	4	3	3	3	3	1	3	1	1	3	1	2	3	3	1	1	4	3	1	3	1	2	3	2	2	3	3	2	2	25,557
495	1	3	4	4	3	1	3	1	1	3	4	4	3	1	2	2	3	2	1	3	1	3	3	2	3	1	3	3	3	4	2	3	3	2	1	3	1	3	2	2	25,573
496	1	1	1	4	3	1	3	3	4	1	3	3	1	3	2	2	4	2	1	3	3	2	3	4	2	3	3	1	3	3	3	4	2	3	3	1	3	2	1	2	25,584
497	3	4	1	1	1	1	3	3	3	3	1	3	4	2	1	4	3	3	4	3	3	1	4	1	2	3	3	3	1	2	2	2	3	3	3	2	1	3	2	2	25,604
498	1	3	4	1	3	1	2	3	3	3	2	3	1	4	3	1	2	1	3	4	3	3	1	1	3	3	2	4	2	3	3	4	3	2	1	3	1	3	2	2	25,616
499	1	1	3	1	3	1	4	1	3	2	3	4	1	4	2	3	3	3	3	2	3	3	1	1	3	2	3	4	2	3	3	4	3	2	3	1	3	1	2	2	25,631
500	1	3	3	3	4	1	3	2	3	2	4	1	4	3	2	3	1	1	3	1	1	1	2	3	4	2	3	3	3	3	3	4	1	3	3	2	3	2	1	2	25,647
501	1	4	2	3	1	1	4	3	3	1	3	2	3	2	1	4	3	1	1	2	3	3	4	2	3	3	3	4	3	1	3	3	3	1	1	3	2	3	2	2	25,663
502	3	1	4	3	1	3	3	1	3	4	1	4	3	1	1	3	3	1	3	3	4	3	2	3	2	4	2	1	2	3	2	3	1	3	2	3	3	2	1	2	25,684
503	3	3	1	1	3	3	1	3	2	1	1	3	4	4	3	3	3	1	1	3	4	2	4	2	2	1	3	2	1	3	3	1	3	3	3	4	2	3	2	2	25,700
504	1	3	1	3	4	4	3	3	3	1	1	4	1	3	2	2	3	3	1	3	1	1	3	2	2	3	4	2	3	3	3	4	2	3	3	1	3	1	2	2	25,711
505	1	4	3	1	3	3	3	3	4	1	3	1	1	1	3	3	2	4	3	2	1	3	3	4	1	3	3	2	3	3	1	4	2	2	3	2	3	2	1	2	25,732
506	3	3	3	1	1	4	3	4	1	3	3	3	3	3	4	1	4	3	3	1	3	1	4	2	1	3	1	2	3	2	2	1	2	3	1	2	3	2	3	2	25,747
507	3	3	4	4	3	1	3	1	3	1	2	2	3	2	4	3	3	3	1	1	1	2	1	4	2	3	3	3	3	3	3	1	4	3	2	3	1	2	1	2	25,759
508	3	4	4	1	1	3	3	4	3	3	1	1	3	1	1	2	3	3	4	2	4	3	1	3	2	2	3	3	1	3	2	3	1	3	1	3	2	3	2	2	25,779
509	1	3	3	1	4	4	1	2	3	2	3	4	1	1	3	1	2	4	1	3	3	3	3	3	3	3	4	3	3	2	1	3	1	3	2	1	2	2	3	2	25,795
510	3	4	1	3	3	1	3	3	1	4	2	3	1	1	2	4	1	3	3	1	4	1	4	3	3	2	2	2	3	3	3	3	2	3	3	1	3	2	1	2	25,811

Table 7-53 Sequence, routings and cost estimates of remanufacturing function (41/44)

Test No.	Quality (q)	Distance (km)	Disassembly sequence (by Part Number)																																											
511	1	0	13	32	17	35	9	15	39	24	38	25	16	21	14	30	11	26	5	10	4	23	22	40	36	7	34	27	3	33	28	20	2	37	29	8	6	19	18	12	31
512	1	100	39	38	14	13	9	5	32	25	17	27	33	35	4	24	26	30	16	11	15	23	28	22	10	20	40	36	7	34	3	21	29	8	37	2	19	18	6	12	31
513	1	200	39	13	27	33	9	15	35	38	40	16	22	11	36	34	25	24	14	30	5	21	17	37	4	20	28	23	3	32	29	2	6	26	10	19	7	18	12	31	8
514	1	300	39	24	35	16	17	38	5	27	14	28	32	30	4	9	13	23	11	15	33	25	40	22	20	26	29	10	36	7	34	8	37	19	21	3	2	18	6	31	12
515	1	400	39	35	14	27	16	36	38	34	33	37	13	25	5	17	4	9	15	24	26	21	30	32	22	20	11	10	3	40	28	23	2	6	29	19	7	8	18	12	31
516	1	500	39	36	24	5	13	14	34	17	37	38	9	35	16	27	33	32	4	28	11	15	3	22	40	21	20	25	26	10	7	8	2	30	23	19	18	29	31	6	12
517	1	600	39	35	5	24	25	13	4	27	9	15	38	16	32	17	26	22	30	21	14	36	11	20	28	33	34	40	37	29	10	7	8	3	23	2	6	19	18	31	12
518	1	700	39	14	24	17	32	5	13	25	26	4	35	16	9	38	30	11	15	22	40	10	36	7	27	21	28	8	34	23	3	37	33	29	20	2	19	6	18	31	12
519	1	800	13	39	9	36	38	17	32	34	16	27	37	11	15	24	40	14	35	5	30	22	33	28	4	25	21	20	3	23	19	29	26	18	2	31	10	6	12	7	8
520	1	900	13	5	25	4	24	9	30	17	39	14	23	16	26	11	10	15	36	7	34	35	3	27	22	8	37	28	19	33	40	29	32	20	38	21	2	18	31	6	12
521	1	1000	13	39	5	32	17	38	9	27	24	4	35	25	11	15	16	22	40	26	20	33	30	28	21	29	14	23	10	36	7	8	34	3	37	2	6	19	18	31	12
522	1	1100	39	13	30	35	17	23	16	25	26	14	9	15	38	22	40	24	20	5	36	34	37	11	4	10	19	7	3	32	27	28	18	31	33	29	8	21	2	6	12
523	1	1200	39	24	27	16	35	9	11	15	36	40	25	14	30	5	4	21	32	22	33	28	17	20	13	26	29	34	38	37	23	10	7	19	3	2	8	6	18	12	31
524	1	1300	13	36	39	30	14	24	27	34	35	9	5	11	15	37	16	17	33	22	32	38	4	20	28	23	3	21	19	29	2	40	25	6	18	31	12	26	10	7	8
525	1	1400	13	25	39	5	24	36	14	30	35	38	16	27	23	9	34	28	11	15	17	40	37	21	19	33	4	32	3	26	10	22	18	7	20	29	2	31	6	8	12
526	1	1500	39	14	27	17	33	36	24	30	23	9	15	11	34	37	35	21	16	5	32	13	38	28	4	25	22	40	26	3	10	20	29	7	8	19	18	2	6	12	31
527	1	1600	39	27	14	16	9	15	17	24	22	38	36	34	5	32	11	30	23	35	13	37	19	18	21	28	33	29	4	40	31	25	20	26	10	3	7	8	2	6	12
528	1	1700	13	27	9	15	33	17	11	24	25	5	4	38	26	14	35	21	16	10	36	7	40	22	34	8	3	37	20	30	23	28	39	2	29	19	6	32	18	31	12
529	1	1800	13	25	17	39	5	27	35	33	14	30	23	24	9	11	15	28	4	16	40	22	20	29	38	26	10	36	7	34	37	32	8	3	19	18	31	21	2	6	12
530	1	1900	39	35	13	17	24	36	27	30	38	32	16	34	33	25	14	37	9	15	28	26	21	23	11	29	22	19	20	5	18	10	4	7	31	3	8	2	6	40	12
531	1	2000	39	36	14	27	33	24	16	13	9	35	30	23	25	32	28	34	29	11	15	17	40	22	21	5	37	20	4	3	2	19	38	18	6	12	26	31	10	7	8
532	1	2100	13	24	30	23	14	17	36	32	27	33	28	35	39	9	15	11	34	38	16	37	19	18	25	40	5	21	22	4	29	26	31	20	3	2	6	10	12	7	8
533	1	2200	39	36	5	27	33	4	35	9	15	11	34	32	17	13	16	14	22	38	25	3	21	30	26	28	23	20	29	37	24	2	40	10	19	6	18	31	7	12	8
534	1	2300	39	9	25	27	28	13	11	15	32	30	24	14	16	40	22	23	35	5	4	21	38	33	36	29	34	17	26	20	10	3	37	19	18	31	2	7	6	12	8
535	1	2400	39	16	24	32	30	36	23	9	27	11	15	17	33	5	25	38	34	37	35	21	14	19	40	22	13	28	29	20	26	10	18	31	7	8	4	3	2	6	12
536	1	2500	13	35	9	17	39	32	14	11	15	30	25	38	26	5	40	16	22	10	36	7	23	4	27	24	20	33	21	34	3	2	8	6	28	37	19	29	18	12	31

Table 7-54 Sequence, routings and cost estimates of remanufacturing function (42/44)

Test No.	Remanufacturing Method (1=Reuse, 2=Reincarnate, 3=Recycle, 4=Disposal)																																										Cost (£)
511	3	1	3	4	1	3	1	3	3	3	1	3	2	1	2	1	4	2	1	3	3	1	4	2	3	4	4	3	2	3	2	3	3	3	3	1	3	2	1	2	23,921
512	1	3	2	3	1	4	1	3	3	4	3	4	1	3	1	1	1	2	3	3	2	3	2	3	1	4	2	3	4	3	3	3	3	2	1	3	3	2	1	2	23,937
513	1	3	4	3	1	3	4	3	1	1	3	2	4	3	3	3	2	1	4	3	3	3	1	3	2	3	4	1	3	2	3	1	2	1	2	3	2	1	3	2	23,957
514	1	3	4	1	3	3	4	4	2	2	1	1	1	1	3	3	2	3	3	3	1	3	3	1	3	2	4	2	3	3	3	1	3	4	2	3	3	1	2	2	23,969
515	1	4	2	4	1	4	3	3	3	3	3	3	4	3	1	1	3	3	1	3	1	1	3	3	2	2	4	1	2	3	2	3	3	1	2	3	3	2	1	2	23,989
516	1	4	3	4	3	2	3	3	3	3	1	4	1	4	3	1	1	2	2	3	4	3	1	3	3	3	1	2	2	3	2	1	3	1	3	3	1	3	2	2	24,005
517	1	4	4	3	3	3	1	4	1	3	3	1	1	3	1	3	1	3	2	4	2	3	2	3	3	1	3	3	2	2	3	4	3	2	3	1	3	1	2	2	24,021
518	1	2	3	3	1	4	3	3	1	1	4	1	1	3	1	2	3	3	1	2	4	2	4	3	2	3	3	3	4	3	3	3	3	2	1	3	3	1	2	2	24,032
519	3	1	1	4	3	3	1	3	1	4	3	2	3	3	1	2	4	4	1	3	3	2	1	3	3	3	4	3	1	3	1	3	2	1	2	3	2	2	3	2	24,053
520	3	4	3	1	3	1	1	3	1	2	3	1	1	2	2	3	4	2	3	4	4	4	3	3	3	2	1	3	1	3	1	3	3	3	2	3	1	3	2	2	24,064
521	3	1	4	1	3	3	1	4	3	1	4	3	2	3	1	3	1	1	3	3	1	2	3	3	2	3	2	4	2	3	3	4	3	2	3	1	3	1	2	2	24,080
522	1	3	1	4	3	3	1	3	1	2	1	3	3	3	1	3	3	4	4	3	3	2	1	2	1	2	4	1	4	2	3	1	3	3	3	3	2	3	2	2	24,100
523	1	3	4	1	4	1	2	3	4	1	3	2	1	4	1	3	1	3	3	2	3	3	3	1	3	3	3	3	3	2	2	1	4	2	3	3	3	2	1	2	24,116
524	3	4	1	1	2	3	4	3	4	1	4	2	3	3	1	3	3	3	1	3	1	3	2	3	4	3	1	3	2	1	3	3	3	1	2	1	2	2	3	2	24,132
525	3	3	1	4	3	4	2	1	4	3	1	4	3	1	3	2	2	3	3	1	3	3	1	3	1	1	4	1	2	3	3	2	3	3	2	1	3	3	2	2	24,148
526	1	2	4	3	3	4	3	1	3	1	3	2	3	3	4	3	1	4	1	3	3	2	1	3	3	1	1	4	2	3	3	2	3	1	3	2	3	2	1	2	24,164
527	1	4	2	1	1	3	3	3	3	3	4	3	4	1	2	1	3	4	3	3	1	3	3	2	3	3	1	1	1	3	3	1	2	4	2	3	2	3	2	2	24,180
528	3	4	1	3	3	3	2	3	3	4	1	3	1	2	4	3	1	2	4	2	1	3	3	3	4	3	3	1	3	2	1	2	3	1	3	1	3	1	2	2	24,191
529	3	3	3	1	4	4	4	3	2	1	3	3	1	2	3	2	1	1	1	3	3	3	3	1	2	4	2	3	3	1	3	4	1	3	1	3	2	3	2	2	24,207
530	1	4	3	3	3	4	4	1	3	1	1	3	3	3	2	3	1	3	2	1	3	3	2	3	3	1	3	4	3	2	1	2	1	4	3	2	3	1	2	2	24,227
531	1	4	2	4	3	3	1	3	1	4	1	3	3	1	2	3	3	2	3	3	1	3	3	4	3	3	1	4	2	1	3	3	3	2	1	1	2	2	3	2	24,243
532	3	3	1	3	2	3	4	1	4	3	2	4	1	1	3	2	3	3	1	3	1	3	3	1	4	3	3	1	3	1	1	3	4	2	3	2	2	2	3	2	24,259
533	1	4	4	4	3	1	4	1	3	2	3	1	3	3	1	2	3	3	3	4	3	1	1	2	3	3	3	3	3	2	1	2	1	3	3	1	2	2	3	2	24,275
534	1	1	3	4	2	3	2	3	1	1	3	2	1	1	3	3	4	4	1	3	3	3	4	3	3	3	1	3	2	4	3	1	3	1	2	2	3	2	3	2	24,291
535	1	1	3	1	1	4	3	1	4	2	3	3	3	4	3	3	3	3	4	3	2	1	1	3	3	2	3	3	1	2	3	1	2	3	1	4	2	3	2	2	24,307
536	3	4	1	3	1	1	2	2	3	1	3	3	1	4	1	1	3	2	4	2	3	1	4	3	3	3	3	3	4	2	3	3	2	3	1	3	3	2	1	2	24,318

Table 7-55 Sequence, routings and cost estimates of remanufacturing function (43/44)

Test No.	Quality (q)	Distance (km)	Disassembly sequence (by Part Number)																																									
537	1	2600	39	35	9	38	11	15	24	17	27	33	36	28	5	30	23	16	4	29	21	34	14	37	40	32	3	19	22	20	2	6	25	18	31	12	13	26	10	7	8
538	1	2700	39	27	38	5	24	9	15	16	13	32	11	25	14	28	33	40	4	22	17	30	23	29	35	20	26	21	10	36	7	8	34	3	37	2	6	19	18	31	12
539	1	2800	13	36	39	30	38	34	37	23	25	14	17	35	26	24	5	9	27	32	33	28	4	29	3	11	15	19	40	16	10	22	7	18	20	31	21	8	2	6	12
540	1	2900	39	13	24	17	14	30	27	23	5	16	25	33	35	38	9	28	11	26	4	10	15	36	7	29	40	8	22	21	32	20	34	3	2	6	37	19	18	12	31
541	1	3000	39	5	16	25	27	33	32	36	35	28	34	38	37	9	15	22	24	40	17	21	14	4	30	3	20	13	26	2	6	29	23	19	18	12	11	10	31	7	8
542	1	3100	13	25	39	5	9	15	16	38	32	11	30	17	27	24	26	28	33	35	14	40	23	10	36	7	29	22	4	20	8	21	34	3	37	2	6	19	18	31	12
543	1	3200	13	27	30	17	32	39	14	28	33	9	29	11	15	24	38	25	23	26	35	21	40	16	5	10	36	7	8	22	4	20	34	37	3	2	6	19	18	12	31
544	1	3300	13	16	25	32	35	5	38	36	39	24	34	9	17	26	27	28	11	15	37	22	30	20	40	21	23	14	33	19	18	29	10	7	4	31	8	3	2	6	12
545	1	3400	39	35	9	15	16	17	24	22	27	40	13	32	30	38	5	25	14	4	20	11	26	28	33	10	29	36	7	8	21	34	23	3	37	19	18	31	2	6	12
546	1	3500	13	17	25	9	27	16	24	28	35	14	26	5	33	32	11	10	15	38	40	4	21	22	20	39	36	7	30	8	29	34	3	37	23	19	2	18	6	31	12
547	1	3600	39	5	14	32	4	36	13	9	15	30	25	17	35	26	38	16	34	27	28	3	40	22	20	24	37	23	19	33	21	29	11	10	7	8	18	31	2	6	12
548	1	3700	13	9	39	38	30	32	27	28	24	11	15	17	25	5	16	23	26	14	4	10	35	22	21	20	40	33	36	7	34	8	29	37	19	3	18	31	2	6	12
549	1	3800	39	25	17	16	24	27	5	13	38	32	28	4	9	14	11	15	26	30	10	22	40	36	7	33	8	29	20	35	34	21	37	23	3	2	6	19	18	31	12
550	1	3900	39	5	24	16	32	30	4	27	14	25	9	17	11	15	13	36	28	35	26	38	22	23	33	29	34	20	21	3	37	10	7	8	40	2	6	19	18	31	12
551	1	4000	39	9	27	14	30	38	35	32	13	16	24	11	17	25	23	26	10	15	36	7	33	21	28	34	37	8	40	29	19	18	31	5	4	3	22	20	2	6	12
552	1	4100	13	17	9	15	38	36	27	32	39	5	40	35	16	28	25	22	30	23	14	26	11	21	20	4	10	7	24	33	8	29	34	3	37	2	6	19	18	31	12
553	1	4200	39	16	27	9	15	5	40	25	32	13	22	38	4	35	14	36	21	11	34	28	33	30	24	3	23	29	17	26	10	7	8	37	19	18	31	20	2	6	12
554	1	4300	13	9	16	27	28	38	30	36	17	25	26	35	32	11	15	24	40	33	5	4	29	34	39	14	23	37	10	3	22	20	21	19	7	18	31	2	8	6	12
555	1	4400	13	5	16	35	17	9	27	38	11	15	14	32	33	4	39	21	25	26	10	22	28	40	24	30	20	29	23	36	7	34	3	2	8	37	6	19	18	12	31
556	1	4500	13	25	32	27	16	38	28	5	24	39	36	17	26	9	15	22	14	4	40	33	30	11	35	34	29	20	37	3	10	21	2	7	6	8	23	19	18	12	31
557	1	4600	39	17	27	36	9	15	25	38	28	34	40	30	13	23	37	14	16	24	35	21	5	26	4	22	20	32	19	3	33	18	29	11	10	7	2	31	6	8	12
558	1	4700	39	36	17	34	9	16	32	35	27	28	14	24	25	5	11	15	4	30	22	40	13	38	23	37	3	19	18	26	10	31	21	20	7	8	33	2	29	6	12
559	1	4800	13	17	25	9	15	35	26	16	27	30	22	23	11	14	5	39	4	33	28	10	32	40	36	7	24	38	20	34	21	3	29	2	37	19	18	8	31	6	12
560	1	4900	13	35	25	9	15	36	14	27	34	11	17	16	38	33	40	24	30	32	37	22	23	21	39	28	29	26	5	10	7	8	4	20	3	19	18	31	2	6	12
561	1	5000	39	27	17	28	32	24	13	5	38	25	35	9	15	11	33	21	26	30	29	23	14	10	16	36	7	4	22	34	40	37	20	19	18	31	3	2	8	6	12

Table 7-56 Sequence, routings and cost estimates of remanufacturing function (44/44)

Test No.	Remanufacturing Method (1=Reuse, 2=Reincarnate, 3=Recycle, 4=Disposal)																																										Cost (£)
537	1	4	1	3	2	3	3	3	4	3	4	2	4	1	3	1	1	3	3	3	2	3	1	1	4	1	3	3	2	3	3	3	1	2	3	1	2	2	3	2	24,339
538	1	4	3	4	3	1	3	1	3	1	2	3	2	2	3	1	1	3	3	1	3	3	4	3	1	3	2	4	2	3	3	4	3	2	3	1	3	1	2	2	24,350
539	3	4	1	1	3	3	3	3	3	2	3	4	1	3	4	1	4	1	3	2	1	3	4	2	3	1	1	1	2	3	2	3	3	1	3	3	2	3	2	2	24,371
540	1	3	3	3	2	1	4	3	4	1	3	3	4	3	1	2	2	1	1	2	3	4	2	3	1	3	3	3	1	3	3	4	2	3	3	1	3	2	1	2	24,382
541	1	4	1	3	4	3	1	4	4	2	3	3	3	1	3	3	3	1	3	3	2	1	1	4	3	3	1	2	3	3	3	1	3	2	2	2	1	2	3	2	24,402
542	3	3	1	4	1	3	1	3	1	2	1	3	4	3	1	2	3	4	2	1	3	2	4	2	3	3	1	3	3	3	3	4	3	2	3	1	3	1	2	2	24,414
543	3	4	1	3	1	1	2	2	3	1	3	2	3	3	3	3	3	1	4	3	1	1	4	2	4	2	3	3	1	3	3	3	4	2	3	1	3	2	1	2	24,430
544	3	1	3	1	4	4	3	4	1	3	3	1	3	1	4	2	2	3	3	3	1	3	1	3	3	2	3	1	3	3	2	2	1	1	3	4	2	3	2	2	24,450
545	1	4	1	3	1	3	3	3	4	1	3	1	1	3	4	3	2	1	3	2	1	2	3	2	3	4	2	3	3	3	3	4	3	1	3	1	2	3	2	2	24,462
546	3	3	3	1	4	1	3	2	4	2	1	4	3	1	2	2	3	3	1	1	3	3	3	1	4	2	1	3	3	3	4	3	3	1	2	3	3	1	2	2	24,477
547	1	4	2	1	1	4	3	1	3	1	3	3	4	1	3	1	3	4	2	4	1	3	3	3	3	3	1	3	3	3	2	2	2	3	3	1	2	3	2	2	24,498
548	3	1	1	3	1	1	4	2	3	2	3	3	3	4	1	3	1	2	1	2	4	3	3	3	1	3	4	2	3	3	3	3	1	4	3	1	2	3	2	2	24,509
549	1	3	3	1	3	4	4	3	3	1	2	1	1	2	2	3	1	1	2	3	1	4	2	3	3	3	3	4	3	3	3	3	4	2	3	1	3	1	2	2	24,525
550	1	4	3	1	1	1	1	4	2	3	1	3	2	3	3	4	2	4	1	3	3	3	3	3	3	3	3	4	3	2	2	3	1	2	3	1	3	1	2	2	24,545
551	1	1	4	2	1	3	4	1	3	1	3	2	3	3	3	1	2	3	4	2	3	3	2	3	3	3	1	3	1	3	1	4	1	4	3	3	2	3	2	2	24,557
552	3	3	1	3	3	4	4	1	1	4	1	4	1	2	3	3	1	3	2	1	2	3	3	1	2	2	3	3	3	3	3	4	3	2	3	1	3	1	2	2	24,577
553	1	1	4	1	3	4	1	3	1	3	3	3	1	4	2	4	3	2	3	2	3	1	3	4	3	3	3	1	2	2	3	3	1	3	1	3	2	3	2	2	24,593
554	3	1	1	4	2	3	1	4	3	3	1	4	1	2	3	3	1	3	4	1	3	3	1	2	3	3	2	4	3	3	3	1	2	3	1	2	3	3	2	2	24,609
555	3	4	1	4	3	1	4	3	2	3	2	1	3	1	1	3	3	1	2	3	2	1	3	1	3	3	3	4	2	3	4	2	3	3	3	1	3	2	1	2	24,621
556	3	3	1	4	1	3	2	4	3	1	4	3	1	1	3	3	2	1	1	3	1	2	4	3	3	3	3	4	2	3	2	2	3	3	3	1	3	2	1	2	24,641
557	1	3	4	4	1	3	3	3	2	3	1	1	3	3	3	2	1	3	4	3	4	1	1	3	3	1	1	4	3	3	3	2	2	2	2	1	3	3	2	2	24,657
558	1	4	3	3	1	1	1	4	4	2	2	3	3	4	2	3	1	1	3	1	3	3	3	3	4	1	3	1	2	1	3	3	2	3	3	2	3	3	2	2	24,673
559	3	3	3	1	3	4	1	1	4	1	3	3	2	2	4	1	1	3	2	2	1	1	4	2	3	3	3	3	3	4	3	2	3	1	3	3	1	3	2	2	24,684
560	3	4	3	1	3	4	2	4	3	2	3	1	3	3	1	3	1	1	3	3	3	3	1	2	3	1	4	2	2	3	1	3	4	1	3	1	2	3	2	2	24,704
561	1	4	3	2	1	3	3	4	3	3	4	1	3	2	3	3	1	1	3	3	2	2	1	4	2	1	3	3	1	3	3	1	3	1	4	2	3	3	2	2	24,716