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Performance measurement and KPIs for remanufacturing

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Abstract

The paper provides a brief background to remanufacturing and the general use of Performance Measurement and Key Performance Indicators (KPIs) before introducing selected and newly formulated KPIs designed specifically for remanufacturing. Their relationships with the remanufacturing challenges faced by two contrasting remanufacturing businesses and the wider reman industry are described in detail.
Subsets of KPIs forming a 'Balanced Scorecard' for each of the two remanufacturing cases conclude the paper. They arise through close working with Centro Ricerche FIAT (CRF) and SKF, and are triangulated by literature review and wider expert interviews.
The two businesses represent contrasting remanufacturing scenarios: well-established high-volume low-margin automotive engine remanufacturing by the OEM (>1000 units per year, < €10 k per unit) verses low-volume high-value wind turbine gearbox reman by an independent start-up (< 100 units per year, > €100 k per unit).
The 10 general production engineering KPIs selected for the reman KPI toolbox are as follows: Work In Progress (WIP), Overall Equipment Effectiveness (OEE), Lead Time (LT), Cycle Time (CT), Hours Per Unit (HPU), Product Margin (PM), Quotation Accuracy (QA), Number of Concessions (NC), Number of managed mBOMs (BOM), and Personnel Saturation (PS).
The Eco KPIs selected are: Material Used (MU), Recycled Material Used (RMU), Direct Energy Consumption (ECD), Indirect Energy Consumption (ECI), Water Withdrawal (WW), Green House Gas emissions (GHG), Total Waste (TW) by weight.
The 8 Remanufacturing KPIs compiled and formulated as part of this research are: Core / Product Ratio (CPR), Core / Product *Value* Ratio (CPV), New Component Costs (NCC), Component Salvage Rate (SRC), Product Salvage Rate (SRP), Core Disposal Rate (CDR), Core Class Accuracy (CCA), and Core Class Distribution (CCD).

Keywords: Remanufacturing; KPI; Key performance indicator; Performance measurement

Background

Remanufacturing has been defined by the UK Centre for Remanufacturing and Reuse as a series of manufacturing steps acting on an end-of-life part or product in order to return it to like-new or better performance, with warranty to match. It continues to be confused with other aspects of the circular economy, such as refurbishment, reconditioning and repairing. However, remanufacturing in itself continues to have immense social, economic and environmental potential if the right measures are set in place to support the industry and its development. It enables *sustained* reuse of products, which can reduce both the cost of producing products, and their environmental impact, e.g. the amount of energy and raw materials used in their production, and the avoidance or postponement of waste sent to landfill.

Key Performance Indicators (KPI) are management techniques employed to enable efficient and effective business monitoring, and are generally acknowledged to be a set of measures critical to the current and future success of any organization [1, 2]. In the view of Parmenter [1] "Performance indicators (PIs) tell you what to do. *K*PIs tell you what to do to increase performance dramatically".

While remanufacturing shares many similarities to traditional manufacturing, such as batch or flow production and the use of machine tools etc., it also contains unique challenges which can render the use of traditional KPIs inadequate for supporting some business goals. These challenges and complexities often include incomplete product knowledge, the need to source, disassemble and inspect cores to identify those suitable for remanufacture, while balancing the uncertain supply chain. Measuring progress against these additional challenges via Key Performance Indicators has appeared in academic research [3, 4] but is underdeveloped industrially, when compared to manufacturing.

The research presented in this paper has been carried out as part of the PREMANUS project (Product Remanufacturing Service System), a European ICT project concerned with developing an on-demand middleware to support End-of-Life decision making and consequent remanufacturing, combining product information and product services within one service-oriented architecture. As the title indicates, the project supports the servitization of remanufacturing [5], and has created the ICT architecture and tools required to do this, particularly supporting strategic and operational decision making (a review of over 40 decision making tools and techniques for remanufacturing is provided by Goodall [6]). The general aim of the work reported in this paper was to design a set of KPI's to assist remanufactures to enhance their businesses performance. Within the project context, these KPIs are being used to measure and validate performance gains during the two industrial pilots.

The following subsection provides a brief background into the use of KPIs, before leading into the Method section, which introduces Kaplan and Norton's well-established 'Balanced Scorecard' approach [7]. The abstracted Results are displayed both as a table of KPIs, and as a diagram representing a remanufacturing 'KPI toolbox', from which scorecards can be produced, tailored for individual remanufacturing scenarios. Scorecards for the two industrial use-cases are presented in the Conclusion section. Between these two sections is a Discussion on how particular reman challenges have led to the selected performance measures.

Introduction to KPIs

This subsection introduces Key Performance Indicators as a fundamental Performance Measurement tool, and outlines common KPIs used in general business scenarios.

KPIs should be used as a management aid to analyse an organization's present performance and to develop strategies for improvement. They must be deployed at the organisational level that has the authority and expertise to take the required action [2]. Authors differ about whether KPIs should be used primarily as a comparison against other organizations or as a comparison over time [1, 2]. Parmenter also states a KPI should ideally be a non-financial measure (i.e. not expressed in terms of currency).

Characteristics of KPIs are [1, 2]:

- **Accountability:** KPIs should be associated with the manager or team responsible for the measure's outcome.
- **Easily assimilated:** KPIs should be quantifiable, accurate, and their meaning understood by everyone within the organization. The measures should be calculated from data which can be readily collected without undue cost.
- **Timely:** KPIs should be measured frequently, reflecting current priorities.
- **Relevant:** The measures should support strategic organizational objectives.
- **Consistent**: KPIs should not conflict with other performance measures.

The optimum number of KPIs is, unanimously in the literature, fewer than 20: Kaplan and Norton [8] recommend fewer than 20 KPIs, Parmenter [1] about 10, while Hope and Fraser [9] and Price Waterhouse Coopers [10] suggest *fewer* than 10 KPIs.

KPIs may be classified into result/driver [11] and lead/lag. KPI measures may consider activity drivers (such as quality, flexibility, resource utilization and innovation) or the results of activities (e.g. competitiveness, financial performance). Lead KPIs predict future performance and enable future trends to be identified. Lag indicators present historical results. Parmenter [1] redefines lead/lag indicators as past-, current-, or future-focused measures. Current measures are monitored daily, past measures over the past week or month and future measures consider initiatives targeting the next day/week/month.

To derive a set of KPIs Price Waterhouse Coopers [10] recommend choosing those measures which the Board uses to manage the business. KPIs should be selected through discussions with stakeholders (employees, managers, customers) [12] and related to the business objectives (strategy) [2, 12] so as to enable progress to be assessed against these objectives both internally and externally [10].

The KPIs should form a balanced set, for example, "measures of efficiency should be set against measures of effectiveness, and measures of cost against quality and user perception" [2]. KPIs should also be placed in context, showing trends as well as the absolute performance [10]. KPIs may change over time as business priorities are revised, and should be reviewed and updated accordingly [2, 10, 13]. Parmenter [1] believes that KPIs should be linked to Balanced Scorecard perspectives (see Methods section).

Methods

The requirements for remanufacture in this project have been collated and identified through various information sources comprising: a literature review, two detailed industrial case studies, formal (two) and informal (two) interviews with industrially-based remanufacturing experts at production manager level or higher, and wider discussions with the industry at a UK parliamentary networking event (2014) and two World Remanufacturing Summits, (USA 2014, The Netherlands 2015). An iterative analysis process was used to establish the KPIs. Based upon the challenges, business priorities and strategies in each area, KPIs were either selected from established published KPIs, or evolved for the specific needs of remanufacturing. Selected KPIs were discussed within the research group and wider consortium and, of course, with the industrial partners themselves, in order to confirm KPI complementarity and minimise conflicts.

The balanced scorecard approach

The methodology adopted for this research is based upon the balanced scorecard approach. This tried-and-tested approach, which provides a framework for translating business strategies into performance measures, was developed by Robert Kaplan and David Norton, and first published in "The Balanced Scorecard – Measures that drive performance" in the Harvard Business Review in 1992 [7]. It built on several decades of prior work in the USA and France and was notable at the time for adding non-financial performance measures to the traditional financial metrics, giving managers a more 'balanced' view of organizational performance. The Balanced Scorecard enables a top down implementation of the company's strategies enabling individuals to understand how productivity supports the overall system. It addresses current and future success, enabling a focus on critical measures and providing a balance between internal measures like operating income, and external measures like new product development. Emphasis on the different perspectives will vary across companies; hence different businesses will require different scorecards [14, 15]. Six areas are included within this study to measure a remanufacturing business, these are;

1. Finance
2. Customers & Quality
3. Internal processes
4. Innovation & improvement
5. Employee satisfaction
6. Environment

Financial goals are linked to growth and profitability. To satisfy customers, goals for timeliness, quality, performance, and service are required. Processes which impact most upon the customer and the company's core competencies should be prioritised. Innovation and improvement activities consider product and process innovation and specific improvement goals. Parmenter [1] adds two extra perspectives: environment and community, and employee satisfaction. Environment and community initiatives feed into customer perceptions and enable links to future employees. The employee perspective considers staff recognition and satisfaction surveys, aiding a positive company culture and enhanced staff retention.

Results

A toolbox of KPIs has been compiled to cover general remanufacturing (Table 1 and Fig. 1) from which a balanced scorecard should be drawn, tailored for individual cases (as in the CRF and SKF use cases described later). In the figures, bordered boxes indicate the reman-specific KPIs compiled and formulated by the author. The general production KPIs recommended are described in Table 2, while recommended environmental (eco) KPIs are listed in Table 3. Datasheets for reman-specific KPIs appear in these tables:

Table 1 Recommended KPI's for remanufacturing

Category	General KPIs (Table 2)	Remanufacturing KPIs (Tables 4–11)
Finance	• Product Margin (PM)	❖ New Component Cost (NCC)
		• Core/Product *Value* Ratio (CPV)
Customers & Quality	➢ Quotation Accuracy (QA)	
	➢ Lead Time (LT)	
	❖ Number of Concessions (NC)	
Process	• Work In Progress (WIP)	• Salvage Rate by Product (SRP)
	• Cycle Time (CT)	❖ Salvage Rate by Component (SRC)
	• Hours Per Unit (HPU)	❖ Core / Product Ratio(CPR)
	❖ Overall Equipment Effectiveness (OEE)	❖ Core Class Distribution (CCD)
Innovation	• Number of Managed mBOMs (BOM)	❖ Core Class Assessment (CCA)
Employee	• Personnel Saturation (PS)	
Environment (Table 5)	❖ Total Waste (TW)	• Core Disposal Rate (CDR)
	❖ Direct Energy Consumption (ECD)	
	○ Indirect Energy Consumption (ECI)	
	○ Materials Used (MU)	
	○ Recycled Materials Used (RMU)	
	○ Water Withdrawal (WW)	
	○ Total GHG emissions (GHG)	

➢ Used by SKF for LoVol/HiVal independent remanufacturing start-up
❖ Used by CRF for established HiVol/LoVal OEM remanufacture
• Used in both remanufacturing scenarios
○ Used by neither remanufacturing scenario but included for completeness

New Components Cost NCC Table 4
Core / Product *Value* Ratio CPV Table 5
Core / Product Ratio CPR Table 6
Core Class Distribution CCD Table 7
Core Class Assessment CCA Table 8
Product Salvage Rate SRP Table 9
Component Salvage Rate SRC Table 10
Core Disposal Rate CDR Table 11

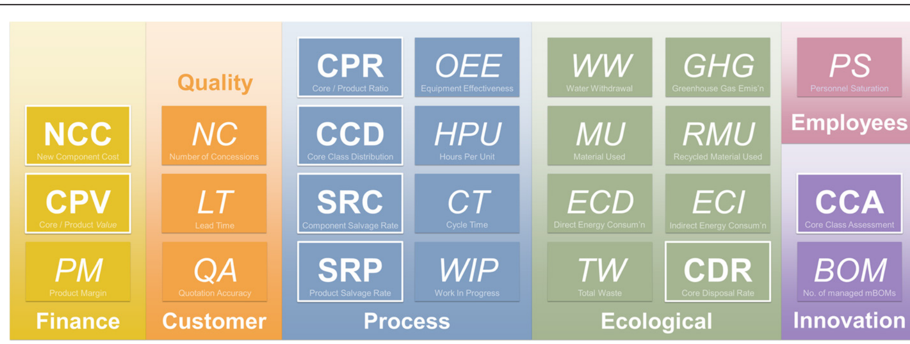

Fig. 1 Full 25 KPI Toolbox for Remanufacturing

Table 2 Recommended General Production KPIs

Finance	
Product Margin (PM)	Margin on each product remanufactured, expressed as a percentage.
Customers	
Quotation Accuracy (QA)	The percentage difference between an estimated cost and the actual cost. Negative values indicate an actual cost turned out to be higher than was estimated; positive values indicate an *over*-estimate.
Lead Time (LT)	Production LT calculated as the time elapsed for specific operations, for example for the assembly stage of products being remanufactured. Order Fulfilment Lead Time is theoretically the total aggregated time from all processes, plus delays.
Quality	
Number of Concessions (NC)	This KPI measures the number of validated requests of component design modification to the OEM. The component design modifications are proposed by the plant to enable the component reuse and increase the salvage. They are validated and maintained centrally by the manufacturing department in an OEM. On the other hand increasing the number of concessions could imply a loss of quality, thus the objective is primarily to monitor the concessions but not promote their increase.
Process	
Work In Progress (WIP)	Cost of cores and components in (and committed to) production, normally including direct labour and manufacturing overheads.
Cycle Time (CT)	Cycle time is the total time from the beginning to the end of a process; usually the whole remanufacturing process.
Hours Per Unit (HPU)	Workload involved in producing the equivalent of one unit of product.
Overall Equipment Effectiveness (OEE)	A set of non-financial metrics which reflect manufacturing success. Measures the extent to which existing machines and equipment are producing the desired or theoretical maximum output. OEE is a high level composite KPI that measures output based on capacity, taking into account process availability, efficiency and quality.
Innovation	
Number of mBOMs (BOM)	The number of manufacturing BOMs managed in the plant. It reflects the size of the portfolio of product families managed in the plant.
Employees	
Personnel Saturation (PS)	Proportion of extra individuals needed to work on a particular product or production line to cover all required operations and skills.

Table 3 Recommended Environmental (Eco) KPIs

Materials Used (MU)	Total amount of material by weight or volume used in remanufacturing, including materials purchased from external suppliers or from internal sources.
Recycled Material Used (RMU)	Total percentage of recycled material used in remanufacturing process, i.e. material which has comes from recycled waste stream.
Direct Energy Consumption (ECD)	Total amount of energy used, derived from primary sources. Use of energy is one of the main drivers of impacts caused by a company's activities.
Indirect Energy Consumption (ECI)	Total amount of energy used, through purchase of electricity, gas, heat, steam etc.
Total Water Withdrawal (WW)	Total volume of water withdrawn for internal use in the company's processes and activities.
Total Green House Gas Emission (GHG)	Greenhouse gas emissions include both direct (gases included in Kyoto Protocol emitted) and indirect (as a result of activities performed by the company). Indirect emissions can be obtained by collecting data from relevant emissions-releasing activities (e.g. electricity use, water supply, fuel used, waste treatment, waste disposal/recycling) and multiplying them for conversion factors (DEFRA, 2012).
Total Waste (TW)	Total weight of waste by type and disposal method.

Table 4 New Components Cost KPI

New Components Cost (NCC)	
KPI Description	This KPI family concerns the cost of new components used during the remanufacturing process. New components can be obtained from a number of sources, here, examples sources from Fiat are ranked from lowest to highest cash cost, and longest to shortest LT:
	• Fiat (OEM) Powertrain plant manufacturing new engines (Powertrain component cost KPIs: Pcc)
	• Fiat (OEM) Spare parts and service department (Aftersales component cost KPIs: Acc)
	• Third party i.e. open market suppliers (Supplier component cost KPIs: Scc)
Purpose (strategic)	Reduce costs by increase salvage rate, through cost visibility, by highlighting external component-sourcing costs.
Calculation	KPIs can be expressed as aggregate costs:
	Sum of the absolute costs for all components from each of the three sources, e.g.:
	• ∑Pcc = total € in a given period
	• ∑Acc = total € for a given remanufactured product
	Or ratios and proportions, e.g.:
	• Scc / total reman costs for a given product = % costs of supplied components in a remanufactured product
	• %Pcc, %Acc, %Scc of remanufactured cores / period = composite % of new components over time
	• ∑Pcc, Acc, Scc / remanufacturing costs / period = new component costs as a proportion of total reman costs over time
Data Source	ERP systems, purchasing and finance systems
Target	Decrease

Discussion

In this section aspects of performance management distinct to remanufacturing are discussed. The particular challenges of remanufacturing in general are presented and discussed first, illustrating some of the background work within the project, with each subsection leading to recommendations for performance measurement approaches and some example solution areas.

Business operations cover most production and supply chain management functions. In remanufacturing there are intrinsic uncertainties in planning, scheduling and control of such functions [16] [17] (stock planning and control, process planning and scheduling, disassembly value, by-products management and matching, reverse-logistics, product knowledge). The three challenges listed below fall within the domains of market supply and demand (Cores, and remanufactured products, respectively), and reverse-logistics.

Table 5 Core / Product *Value* Ratio KPI

Core / Product *Value* Ratio (CPV)	
KPI Description	This KPI measures the ratio of the Cost of the Cores at the point of acquisition, and the Price at which the remanufactured Product is sold.
Purpose (strategic)	Ensure sourcing of high value cores.
Calculation	CPV = (∑ CoreCost(i)/ProductPrice(i))/n
	Where i is the selected product, from n products
Data Source	Sales systems and production management systems
Target	Below 1 and falling, to an equilibrium with NCC (and others)

Table 6 Core / Product Ratio KPI

Core / Product Ratio (CPR)	
KPI Description	This KPI tracks the average number of cores used to produce one remanufactured product (or equivalent). It considers Work in Progress and stock-piled mid-build products as well as output, therefore reflecting current status, and enabling use as a live / tracking KPI where the data streams exist, as well as a more traditional summative / retrospective KPI for periodic review. The objective is to decrease the number of cores processed for a given output; the number of finished remanufactured products. The inverse, the Product / Core Ratio (PCR), can be used instead, in the form of a percentage or indicative fraction of a remanufactured product produced for each Core processed with in the plant. Although the advantages of either metric over the other are quite subtle, the recommendation is that CPR, being focussed around the product rather than the core, is conceptually simpler and creates a stronger message, i.e.: CPR 1.8 "We have to process almost 2 cores for each product we can sell", or PCR 55 % "From each Core we process we get just over half a product" PCR as a percentage < 100 % offers another way of abstracting Core value away from absolute cash cost.
Purpose (strategic)	Encouraging the sourcing of higher-quality cores. Also rewards improvements in remanufacturing process efficiency, but should be carefully considered and balanced with process time and cost e.g. the Hour Per Unit KPI.
Calculation	$CPR = \frac{C}{P+S+WIP}$ $PCR = \frac{P+S+WIP}{C}$ C = Cores processed, P = Products shipped, S = Stocked mid-build products, WIP = Work-in-Progress
Data Source	Sales systems and production management systems
Target	1 (one)

Supply, demand, and reverse logistics

Uncertain core arrival time

Although there are no universal patterns for the availability of Cores across industries and geographical boundaries, there are specific patterns for specific industries or businesses. For instance, wind turbine related remanufacturing sees Core availability rise outside windy seasons, when wind farms are less productive.

There are also many ways to provide incentives to smoothing Core availability times, for instance, by replacement or return discount methods. The ideal is to smooth out peaks and troughs of Core arrival time so that efficient capacity planning can be achieved.

Table 7 Core Class Distribution KPI

Core Class Distribution (CCD)	
KPI Description	The KPI displays the Core Class Distribution for selected products. For incoming products, it gives an indication of the value of the Cores in stock. During remanufacturing, it indicates the value of the WIP. The objective is to increases the number of Class A cores.
Purpose (strategic)	Improve value of cores in stock Improve WIP value
Calculation	CCD = (1.00 × number of Class A cores + 0.30 × number of Class B cores + 0.15 × number of Class C cores) / total number of cores
Data Source	Production management systems
Target	1 (one)

Table 8 Core Class Assessment KPI

Core Class Assessment (CCA)				
KPI Description	Accuracy of the process of estimating core quality and condition. Differences between initial estimates and actual core class assignment (after disassembly and inspection) are aggregated.			
	CRF use the following Core classes:			
	A: complete, B: incomplete, C: incomplete with major flaw.			
	Other remanufacturing businesses use similar simplified techniques, while some (especially high value product operations) bypass this step completely, some moving straight to cost and time estimations.			
	In the case of CRF, an estimated Core Class will be computed remotely (using product-usage metrics). The Core Class is then *assigned* at the engine entrance in the plant, and revised after disassembly and inspection. The case of class under-estimation indicates lower product value, an inaccurate model, and potential loss of opportunities. The case of class over-estimation indicates added costs or lost resource. A penalty index is given to every accuracy error, with a higher penalty index given to negative values (penalising the sourcing of low-value cores).			
Purpose (strategic)	Ensure sourcing of high value cores & accurate forecasting			
Calculation	$CCA = \sum CCA(i) \times p(i)$			
	$CCA(i) = \text{Actual CC}(i) - \text{Estimated CC}(i)$			
	$\text{Core Classes}: \ A = 100, \ B = 70, \ C = 10$			
	CCA	p	CCA	p
	−30	−2	30	1
	−60	−4	60	2
	−90	−6	90	3
Data Source	Sales systems and production management systems			
Target	0 (zero)			

A ‘Core supply smoothness’ KPI would be useful to some businesses, and could be based upon the standard deviation of elapsed time between Core arrivals (in a suitable metric, e.g. days, weeks, months). Potential solutions include the right mix of ‘make to stock’ and ‘make to order’ [18].

Uncertain product demand

This uncertainty directly affects price, quantity, and availability of remanufactured products. There are ways to smooth demand patterns by building stable customer

Table 9 Product Salvage Rate KPI

Product Salvage Rate (SRP)	
KPI Description	This KPI measures the percentage of reused components in a product, family of products, or a moving average of all products.
Purpose (strategic)	Improve plant RoI by decreasing total remanufacturing costs.
	An excellent overall KPI influenced by many factors and also useful if used as a P-KPI for identifying those products or product families most successfully remanufactured.
Calculation	Product level: Product Salvage Rate (SRP):
	$SRP(i) = r \times \sum SRP(j)$
	Where i is the product and j is a main components of the product r is the percentage of the main component costs with respect to the total product costs
	Operational level: Overall Product Salvage Rate (OSRP):
	$OSRP(i) = mean(\sum SRP(i))$
	Where i is the instance in a set of selected products
Data Source	Production management systems
Target	100 %

Table 10 Component Salvage Rate KPI

Component Salvage Rate (SRC)	
KPI Description	This KPI measures the percentage of components and/or subassemblies salvaged. The higher this percentage, normally the lower the total cost of remanufacturing, due to minimising purchasing costs. Some remanufacturers include salvaged components as those that are placed in stock; most only include components that end up on shipped products. If used in tandem with a stock efficiency KPI and/or NCC, the latter can be an effective general measure; however the former is preferable if a metric focussed on component salvageability is required.
Purpose (strategic)	Improve plant RoI by decreasing total remanufacturing costs.
Calculation	SRC(i) = Number of reused components of type i / total number of these components entering the plant
Data Source	Production management systems
Target	100 %

relationship and implementing a lean production philosophy [19] to reduce cost while maintaining quality. The study of demand pattern here is fundamental. Core Cost / Product Price (simplified to Core / Product *Value* ratio, or CPV) will provide a catch-all KPI encompassing many of these market factors (dependent as it is on the cost of acquiring cores and the price achieved for remanufactured products, alongside general production efficiency). Relevant KPIs could also draw from missed sales (or value) due to e.g. price mismatch, limited stock, long lead time, inadequate warranty, lean metrics such as stock level, and quality measures such as the number of customer complaints and returned products within warranty.

Uncertain logistics costs

Most of this group of uncertainties are intrinsic to the remanufacturing industry. The relevant contributing process Performance Indicators include the specific costs and times related to collection, storage, disassembly, washing and inspection.

For businesses beyond a certain scale, solutions may lie in utilising buffer storage to enable batch processing through disassembly-cleaning-inspection etc. via intelligent

Table 11 Core Disposal Rate KPI

Core Disposal Rate (CDR)	
KPI Description	The percentage mass of cores which do not get remanufactured or whose components are not salvaged or sold on. Components sold for material recycling *are* included in this remanufacturing-specific version of the Mass Balance KPI.
Purpose (strategic)	The overall objective is to maximise profitability while minimising environmental impact, through reflecting the effectiveness of the: • Remanufacturing process • Core acquisition process • Scrap material processing and sales process
Calculation	Expressed as a percentage of the mass of incoming Core material which is not sold or recycled. CDR = Waste/(Mass of Incoming Cores + Mass of New Components) Waste = Mass of Incoming Cores – Mass of Invoiced Goods (Mass of Invoiced Goods includes: remanufactured products and components, components sold unprocessed and for recycling)
Data Source	Sales and purchasing databases, MES, waste handling contractors.
Target	Falling target. When remanufacturing, Core acquisition, and scrap material sales processes are optimal, CDR becomes a stable target.

production grouping [20]. Success in this area will be reflected in many of the higher level general production engineering KPIs listed in the previous section, such as Hours Per Unit and Personnel Saturation.

Uncertain core condition

There has been substantial progress in monitoring and recording operational condition during the use-phase of a product's lifecycle (collecting field data). However, due to a combination of complexity in operational environments, a lack of effective technologies in covering the complexity, and a lack of apparent economic incentives, such efforts often run short of providing full information on the conditions of the cores.

Core condition is a very important factor in remanufacturing, and many relevant KPIs can be deployed to cover the range of Core-related activity.

The PREMANUS project is enabling early Core condition assessment based on a combination of integrated condition monitoring, field data, in-situ inspection, and intelligent analysis of historic data for a range of similar products. In order to streamline high-volume remanufacturing operations, 'classes' or quality bands will often be employed. Improving the accuracy of this process would be monitored through a Core Class Assessment (CCA) or similar KPI.

Monitoring the success of the Core acquisition process, with the aim of maximising the proportion of high value Cores will be tracked through a Core Class Distribution (CCD) KPI. Cores can be at the centre of (or at least a reference for) measuring the efficiency of other remanufacturing processes, such as waste disposal, through a Core Disposal Rate (CDR) KPI, also encouraging improved environmental performance.

Potential solutions being developed within the project include a quick and basic condition inspection (before the often lengthy complete disassembly cleaning and inspection process), combined with strategic use of incomplete product life data. The success of these solutions and, again, the wider remanufacturing process can be tracked through variance in the Core / Product *Value* Ratio (CPV) KPI. Warning of a decline in on-going Core condition would be triggered by increases in the New Component Cost (NCC) and Core / Product Ratio (CPR) KPIs.

Uncertain disassembly level

With familiar cores (via either the OEM or knowledge gathering during previous exposure recorded at disassembly), one can plan the economically appropriate level of disassembly for each model based on; subassembly condition, component value, replacement value / time, and disassembling process costs, plus risks / value of damage in disassembly.

If possible, performance measures for cost and time should be calculated for discrete stages in the disassembly process, via an Activity Based Costing or similar methodology, but focussing on the cost of new component sourcing and man-hours before, and only if necessary, considering materials, consumables and allocated overheads.

Uncertain disassembly / assembly processes required, depending on the condition of components, is a sub problem of the above disassembly-level challenge, but focusing on process aspects. It might also affect and be affected by workstation layout, operator deployment and other factors. Potential KPIs include remanufacturing Lead Time (LT), OEE, and workstation/operator idle time.

Short notice period of component demand

In remanufacturing, defective components are often only discovered after disassembly, cleaning and inspection. There is then pressure to replace these components as soon as possible (through repair or replacement) in order to minimise Lead Time (LT) and Work in Progress (WIP), but often with a cost penalty.

There are ways to solve the problem. Pre-disassembly inspection (such as endoscopic inspection) and Lifecycle Management information analysis belong to a group of information related solutions; spare component / Core stock management belongs to another category of buffering techniques; but are also information related.

The most relevant high level KPI is Lead Time but this is affected by a great many factors and only by activities on critical paths. New Component Cost (NCC) is a useful mediating indicator, as sourcing new components is often the expensive 'solution' to achieving short lead times. Salvage Rate by Component (SRC) will highlight successful sourcing of used or reworked components from stock. A more focussed KPI that considers 'accuracy of predicted component need' (maximise), and 'time between component need prediction and point of assembly' (also maximise) is also recommended, to target this particular problem.

Benefit and cost indices can also be used to respectively encourage knowledge management activities and penalise responsive rather than pro-active decisions. These can include factors such as:

- The value gained through retaining and using product design information (for independent, non-OEM remanufacturers)
- The value of using product life cycle information to predict component demand
- The cost penalty attributed to a delay or long lead times

Uncertain quantity of salvaged components

If a disassembled Core is not remanufactured its salvageable components may be retained, therefore uncertainty is most related to stock decisions and level control. For established remanufacturing businesses, the recurrence of certain models of Core should be apparent. In these cases the most relevant measurements concern the time held in stock or rate of reuse for particular salvaged components. These can also be aggregated to give an overall view of stock performance, with the value of salvaged component stock also calculated as a complimentary measure.

The two KPIs that will be most useful in monitoring improvements here are New Component Cost (NCC) and Core / Product Ratio (CPR). NCC measures the cost and source of new components needed to complete the remanufacture of products, and will reduce as the use of salvaged components increases (in this case, as a result of having the right components available from stock on demand).

CPR indicates how many Cores are processed to produce each remanufactured product. This reveals the number of components coming into the system (e.g. a CPR of 2 would indicate a surplus of 1 set of components for every 2 Cores entering the system). Salvage Rate by Component (SRC) is an important compliment to this and also a useful feed into stock management performance measurement, indicating which components are most salvageable.

Conclusions

The following sections summarise the requirements and related KPIs prioritised by an independent (non-OEM) wind turbine gearbox remanufacturing business pilot, and by the research arm of an automotive OEM for its established engine remanufacturing plant.

Wind turbine gearbox remanufacturing at SKF (Fig. 2)

This use-case represents three distinctive business and production scenarios:

- Low-volume, high-value (< 100 units per year, > €100 k per reman unit)
- Non-OEM products (not SKF Cores, no official partnership with gearbox OEMs)
- Start-up business (business unit started as a one-year feasibility study)

In contrast, high-volume remanufacturers (> 1000 units per year) can often look to small efficiencies gained in repetitive production processes that, when multiplied by high volumes, provide worthwhile cost savings, and an acceptable return on investment. These industries, such as automotive, often have particularly small margins on the manufacture of components, due to the maturity and competitiveness of the sector.

Project and batch production operations, such as low-volume high-value asset remanufacturing, often have the opportunity to look elsewhere to maximise profit (e.g. by maximising sales price through differentiated and value-added offerings). This is especially true in industries that are still developing, such as remanufacturing. The quoting process is much more important here, as obviously there is a lot more at stake when profit comes from a small number of high-value projects. Also related is the need to build customer relationships – a critical process for start-ups. Estimate accuracy is the main concern here, with customer lead-time (LT) also important. Building supplier relationships and, later, integrated supply chains, would be the next priority. Knowledge management is especially important with independent start-up remanufacturers. KPIs measuring rate or frequency of knowledge re-use, and the value gained by it should be investigated.

The low volumes enable the business priorities listed in Table 12 to be addressed. The associated KPIs can be recorded for both individual units (product instances) and aggregated to calculate the average values for product types, families or for remanufacturing processes. Many of the business priorities can be KPIs in their own right (see

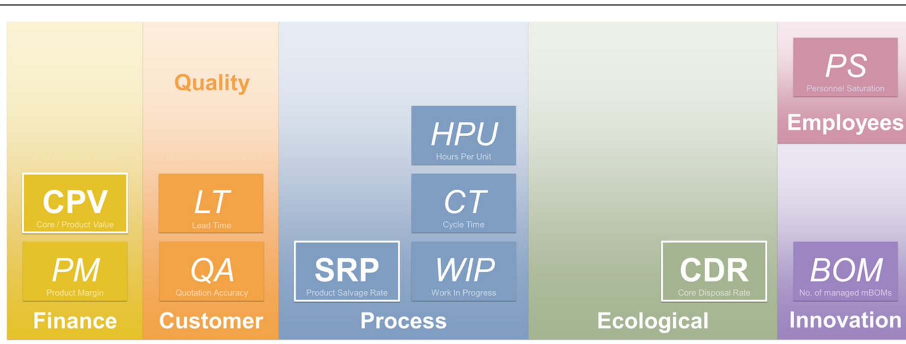

Fig. 2 SKF 11-KPI Scorecard: LoVol / HiVal independent reman start-up

Table 12 Priorities and KPIs for LoVol/HiVal independent remanufacturing start-up

Finance	Innovation
Margin: *PM*, CPV	Adaptability: *BOM*
Revenue: (*HPU*, *WIP*, SRP)	
Customers & Quality	Employee
Success rate for offers: *QA*, (*BOM*)	Utilisation: *PS*
Response time to customer: *LT*	Knowledge sharing: *PS*, (*BOM*)
Processes	Environmental
Throughput time: *CT*	Waste: CDR
Technical errors: *HPU*	
SRP, *WIP*	

Background section) but the more-specific, further-reaching and easier-to-calculate KPIs listed are those recommended.

Automotive-class engine remanufacturing at Fiat (Fig. 3)

The CRF / Fiat remanufacturing use-case is characterised by the following features:

- High-volume, low-value (< €10 k per unit, > 1000 units per year)
- OEM products (carried out by or in close partnership with the Core OEM)
- Established businesses (> 10 years)

In addition to a standard set of high level business KPIs (Table 13), specific process KPIs defined as technical or product KPIs are aggregated according to criteria such as the period, the family of engine, or remanufacturing phase. Plant managers compare the price at which a Core is acquired with its estimated value on arrival at the plant, and again after disassembly and full inspection. Core / Product *Value* Ratio (CPV) can be calculated and used at this product instance level, as well as a good catch-all medium-term monitoring KPI for both general plant performance and to track trends in product families.

Most other process KPIs are taken from general production engineering: Overall Equipment Effectiveness, an old but still common hierarchy of metrics to evaluate how effectively a manufacturing operation is utilized; Work-In-Progress to encourage

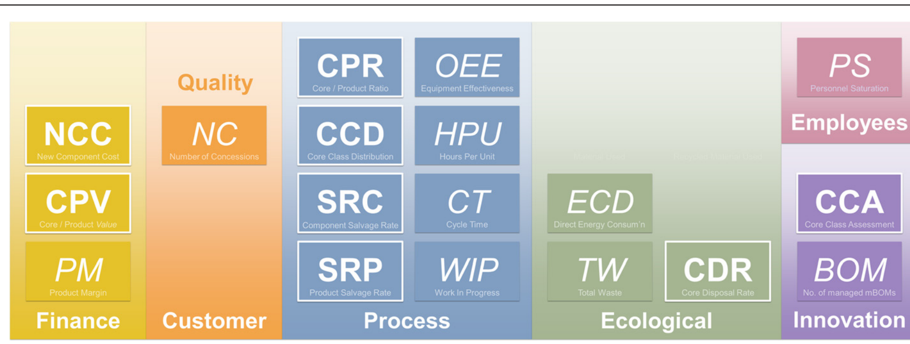

Fig. 3 CRF 18-KPI scorecard: Established HiVol / LoVal OEM remanufacturer

Table 13 Priorities and KPIs for established HiVol/LoVal OEM remanufacturer

Finance	Innovation
Net engine margin: *PM*, CPV, (*OEE*)	Adaptability: *BOM*
Revenue: (*HPU*, *WIP*, SRP)	Core management: CCA, (CCD, CPR)
Purchasing costs: NCC	
Customers & Quality	Employee
Offering: (*BOM*)	Utilisation: *PS*
NC	Knowledge sharing: *PS*, (*BOM*)
Processes	Environmental
Throughput: *CT*	Scrap rate: CDR, *TW*
Technical errors: *HPU*, (*NC*)	Energy: *ECD*
Salvage: SRC, SRP	
OEE, *WIP*, CPR, CCD	

reduction in the immobilised capital (Cores, engine bases, semi-assembled engines and components); Number of concessions (also called exceptions); Cycle-time, of specific operations or the whole reman process; and Number of Managed mBOMs, measuring the number of product families managed in the plant and reflecting a multitude of cross-category benefits (e.g. flexibility, workforce training, customer responsiveness).

Reman-specific KPIs focus around core/product and salvage ratios. The broad objective to decrease the number of Cores acquired with respect to the number of engines remanufactured is monitored at high level, via Core / Product Ratio, and at a more detailed level via Salvage Rate. Either or both an *engine* perspective (percentage of salvage for each, or a specific family of remanufactured engine) or a *component* perspective (percentage of each component salvaged for remanufacturing) can be useful. In all three cases, the objective should be to increase the ratio of reused components over new components in the remanufactured engine, leveraging the incoming cores quality.

Core acquisition quality management is a particular focus of CRF (but not necessarily typical of the industry). It requires separate monitoring, via a custom-made 'Core Class Distribution' KPI. Aggregating over several Cores, the objective is to increase the percentage of Class 'A' Cores (highest quality) with respect to other classes.

Abbreviations

BOM: Bill of Materials; CCA: Core Class Assessment; CCD: Core Class Distribution; CDR: Core Disposal Rate; CPR: Core / Product Ratio; CT: Cycle Time; CPV: Core / Product Value (Ratio); HPU: Hours Per Unit; ICT: Information and Communication Technology; KPI: Key Performance Indicator; LCA: Life Cycle Analysis; LT: Lead Time; NC: Number of Concessions; NCC: New Component Costs (and Source); OEE: Overall Equipment Effectiveness; PM: Product Margin; PS: Personnel Saturation; QA: Quotation Accuracy; SRC: Component Salvage Rate; SRP: Product Salvage Rate; WIP: Work In Progress.

Authors' contributions

IG carried out the majority of the research, analysis, KPI formulation and editorial work. PG assisted throughout the project, specifically with the interviews and the paper's production, CP provided introduction and method section drafts, and YP provided the discussion section draft. AW and PC advise on the project and were involved in its conception. JM and FD established the pre-project performance measurement strategies within their respective companies. All authors read and approved the final manuscript.

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