Development of System Models for Industrial Processes Selection with regard to Product Lifecycle Extension (PLETS Models)

Von der Fakultät für Umweltwissenschaften und Verfahrenstechnik der Brandenburgischen Technischen Universität Cottbus zur Erlangung des akademischen Grades eines Doktor-Ingenieurs **(Dr.-Ing.)** genehmigte Dissertation

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Abstract

DUNMADE, ISRAEL:

DEVELOPMENT OF SYSTEM MODELS FOR INDUSTRIAL PROCESSES SELECTION WITH REGARD TO PRODUCT LIFE EXTENSION

PLETS (Product Lifecycle Extension Technique/Process Selection) model is a computer supported decision making analysis method developed for the management of mechanical products at the utilisation and retirement stages. The core of the work involves the hybridisation of a number of classical MADM methods to suit decision making in the product life extension domain. The model provides a comprehensive view of the economic implications, technical requirements and environmental effects of using one of the five identified lifecycle-extension-processes (PLETs): repair, refurbishing, remanufacturing, upgrading and cascading, to elongate the service life of a given hardware. The PLETS model is intended for the evaluation and screening of PLETs, and for the selection of the best option under a given scenario. The results obtained for the shelling machine used to illustrate the applicability, and to validate both the methodology and its companion demonstrative computer implementation prototype showed that repair is the best PLET under the given conditions. The compatibility of this result with what obtains in practice shows that the methodology is a suitable decision making aid for product life extension.

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Table of Contents

List of Nomenclature

$actvy$	Activity 1,2,…, N_{actvy} (unscrew, remove, etc.) making up a constituent operation
AMETIDE	A MEthodology for TIme Disassembly Estimation
a_t	Allowable delay as percentage of workday
BDI Range	Boothroyd Dewhurst Inc. developed DFE software package
c_{acq}	Acquisition cost per unit retired product in DM/acquired product
c_{adm}	Administrative cost element value
$(c_{adm})_{typ}$	Administrative cost element type
C_{ADV}	Advertising cost
C_{AO}	Administrative expenses
C_{ASO}	Administrative and selling expenses/overhead
c_c	Cost category (such as direct material cost, factory overhead) value per unit product for each operation of the process in DM/unit product
C_{DL}	Direct labour cost
C_{DM}	Direct material cost
C_{DRT}	Direct costs
c_{efo}	Factory operating cost element value
C_{FO}	Factory overhead
C_{FTR}	Factory cost
C_i	Total cost category value incurred in the period under consideration
C_{IDL}	Indirect labour cost
C_{IDM}	Indirect material cost
C_{IRSC}	Infrastructure related sales cost
$clmd$	Cleaning methods 1,2,..., N_{clmd} (spraying, grinding, etc) utilised.
$(c_{lr})_{typ}$	Other labour related cost type per period in DM
$(C_{max})_{op}$	Maximum allowable cost in the department/operation
C_{MUC}	Machinery utilisation cost
C_{OLR}	Other labour related costs
C_{opc}	Total costs of any outside processing such as transportation charges, including freight, insurance, storage, customs, duty charges and labour charge as well as other expenses on the material in DM
C_{OPE}	Operating expenses
C_{OVH}	Overhead cost
C_{PLET}	Process cost per unit reworked product
$cptr$	Competitor 1,2,…N_{cptr}
c_{rtd}	Unit cost of retired product in DM/retired product
C_{RWG}	Cost of reworked goods
c_{slt}	Sales cost element value

C_{SO}	Sales overhead
c_{st}	Sales tax per unit retired product
C_{SUC}	Sales utilities cost
ct	Indirect labour categories 1,2,..., N_{ct}
C_{tim}	Amount expended on individual cost element on the quantity of indirect material in the period under consideration
C_{UMFT}	Utility consumption cost
d_{effl}	Density of the liquid effluent
d_{gsem}	Density of the gases emitted
d_{alld}	Standard dimensional specification type, *typ* that meets the required product quality.
$(dcr_{pr})_{typ}$	Dimensional conformity rating of the material or part with respect to the dimensional type (diameter, length,…)
dcs_{pr}	Dimensional conformity score of the part or material
d_{op}	Degree of the operations' intensity
d_{rqd}	Type of dimensional specification (type) *typ* of the part or material *pr* needed for the product quality (nearest to d_{sp})
d_{sp}	Dimensional standard specification (type) *typ* of the part or material *pr* available on the market
d_{spp}	Dimensional specification type, *typ* for the PLET option finished product
d_{spr}	Dimensional standard specification type, *typ* for the part or material *pr* available on the market
dv	Device type 1,2,…N_{dv} used in the department
E_{ACSV}	Gas conservation value
E_{ARCOSP}	Air consumption per product
E_{CAGC}	Compressed air or gas consumption
ecr_{rwd}	Conformity rating of the product in terms of an ecological parameter
E_{ec}	Total wattage of all facilities used for reworking the period
E_{ECSV}	Energy conservation value
E_{ECV}	Electrical energy consumption per unit product
EDIT	Environmental Design Industrial Template
E_{EECSV}	Electrical energy conserved per product
E_{flt}	Quantity of fuel type consumed per period
eis_{rwd}	Eco-index standard for reworked product with regard to the parameter
eiv_{rwd}	Eco-index (durability, resource consumption rate, emission,…)value of the reworked product with regard to the parameter
E_{ele}	Electrical consumption in the period under consideration
E_{ELEC}	Electrical energy consumption
E_{eler}	Electricity consumption per period read from measuring device
E_{Elerpp}	Electric energy required to manufacture a virgin product

E_{FCSV}	Quantity of fuel conserved per product
E_{FECU}	Fuel energy consumption per unit
E_{Ferpp}	Fuel energy required to manufacture a virgin product
E_{flt}	Quantity of fuel type consumed per period
E_{FTCU}	Fuel energy type consumption per unit product
E_{FUEC}	Fuel energy consumption
E_{Grpp}	Quantity of gas/compressed air required to manufacture a virgin product
E_{GSEFP}	Quantity of gas emitted per unit product
E_{IMAS}	Impact assessment score
E_{IWR}	Waste release impact
ELECTRE	Elimination et Choice Translating Reality method
E_{LEDFP}	Liquid effluents discharged from the process per product
E_{MCSV}	Total material conservation value per product
E_{NTMC}	Non-toxic material consumption
E_{OCSV}	Other resources conserved
E_{PLET}	Environmental attribute score of the PLET
E_{RCSM}	Resource consumption
E_{RCSV}	Resources conserved
E_{RTMC}	Toxic material content reduction
$(escr_{pr})_{typ}$	Part or material's conformity rating on ecological type's standard
E_{SWGFP}	Quantity of solid waste generated from the process per product
E_{TMC}	Toxic material content
E_{WCSV}	Water conservation value
E_{WR}	Total quantity of waste generated per product
E_{Wrpp}	Quantity of water required to manufacture a virgin product
E_{WTRC}	Water consumption
E_{WTRCP}	Water consumption per product
flt	Fuel types 1,2,…, N_{flt} (Petrol, diesel, coal, coke, etc.)
fl	Flexible or permissible requirement
GE Manual	GE Plastics Design for Recycling Manual
ifl	Under inflexible condition
$inovtyp$	Innovation/novelty type 1, 2, ..., $N_{inovtyp}$ (improved performance, etc.)
$(iscr_{pr})_{typ}$	Ideal safety conformity score of a part or material
jt	Matings/joints/connections 1, 2,..., N_{jt}
l	Liaisons, it is also referred to as connectors
L	Material losses arising from the process used
LASeR	Life-cycle Assembly, Service and Recycling software
LD_{50}	Lethal dose of the waste constituent type

$(L_{dnir})_{typ}$	Negative index rating of the index type considered under desired condition
L_{DNIS}	Desired negative indices goals conformity score of the PLET
L_{dpir}	Positive legislative index rating under desired condition
L_{DPIS}	Desired positive indices goals conformity score of the PLET
L_{MNIS}	Negative legislative score of the PLET under mandatory condition
$(L_{mnir})_{typ}$	Individual negative index (toxic material consumption, emissions,…) rating of the PLET under mandatory condition
L_{MPIS}	Positive legislative score of the PLET under mandatory condition
L_{nig}	Quantity of pollutant type emission or toxic material type/ resource consumption goal aimed at
L_{niv}	Quantity of emission of pollutant type or consumption of toxic material type/resource by the process
L_{pig}	Quantity of components reuse or value of environmental performance standard type goal aimed at
L_{Pir}	Positive legislative index rating under mandatory condition
$(L_{Pir})_{typ}$	Individual positive index rating of the PLET under mandatory condition
L_{piv}	Quantity of components reuse or value of environmental performance standard type achieved
m	Machine type/variety 1,2,..., N_m used in the operation unit of the process
MADM	Multiple Attribute Decision Making
M_{dci}	Dimensional conformity index of the PLET
M_{DMD}	Demand score of the PLET reprocessed product
M_{dni}	Demand nature index
M_{dqs}	Quantity of demand rating
M_{DQT}	Demand quantity score
M_{dvof}	Demand volume score
M_{esci}	Ecological specification conformity index of the parts and materials needed by the PLET option
M_{fbmds}	Flexibility in the demanded dimensional specifications
M_{fcs}	Frequency of change in government rating
$_{mft}$	With regard to the factory/processing
M_{ips}	Internal peace and security rating
M_{irs}	International relation rating
m_{mop}	Machine type involved in the operation
$_{mod}$	Functional modules 1, 2, ..., N_{mod}
M_{OSI}	Other supply indices
M_{pci}	Performance conformity index
$(M_{pcr})_{rwd}$	Conformity rating of the product in terms of a performance parameter
M_{pcsp}	Performance conformity score of the product
M_{PROMI}	Production mode index

$(M_{promos})_{pr}$	Production mode (custom-produce, mass-produce,…) score of the part or material type *pr*
M_{POSTI}	Purchasing market political stability supply quantity index
M_{sci}	Safety conformity score for the PLET option
$(mscr_{pr})_{typ}$	Minimum safety score of the specification type (tensile strength, shear strength, torsion,…) *typ* for the part or material
M_{sdf}	Seasonality of demand
M_{SQL}	Supply quality score
M_{SQT}	Supply quantity score
M_{SS}	Seasonality of supply score
M_{SUP}	Supply score of resources required by the PLET to reprocessed the product
M_{SVL}	Supply volume
$_{mtd}$	Methods 1, 2, ..., N_{mtd} (wrapping, 'cartoning', etc.)
$(m_t)_m$	The utilisation rating of a machine type *m* in DM/min
M_{wor}	Workability index
NADL	Non-value added direct labour
N_{ald}	Number of variations in the particular specification type allowed by the market with respect to the part or material
N_{alld}	Number of variations in the particular specification type allowed by the market with respect to the product
N_{avp}	Number of variations in the particular product specification type available
N_{avr}	Number of variations in the particular specification type available with respect the part or material
N_{clmd}	Number of cleaning methods 'combinedly' utilised
N_{ct}	Number of labour categories
N_{dv}	Number of the types of devices used in the department
$N_{inovtyp}$	Number of innovation/novelty types considered
N_{jt}	Total number of matings/joints per product
N_l	Number or quantity of the specific type of liaisons
N_{ltyp}	Number of variety of liaisons
N_m	Number of machine types used in the process
N_m^d	Number of months in a year in which the product is demanded
N_{mop}	Number of the particular machine type *m* involved in the operation
N_{mr}	Months in a year in which the part/material type *pr* is supplied
N_{mtd}	Number of methods used/making up the (packaging) operation
N_{op}	Number of operations
N_p	Number of units produced per period
N_{pr}	Number of part or raw material types involved
N_r	Number of (non-toxic) material types needed/being used in the PLET option for the product
N_{recmd}	Number of reconditioning methods combined
$N_{resutyp}$	Number of resource types considered
N_{rjt}	Average number of reusable matings/joints per product

$N_{rwd,}$ n_{rwd}	Number of products to be reworked
N_{somd}	Number of sorting methods combined/utilised
N_{tesmd}	Number of test methods combined/utilised
N_{tim}	Number of the particular individual cost element of indirect material
$(N_t)_m$	Number (quantity) of a machine type *m* involved in the operation *op*
N_{typ}	Number of types
N_{typdv}	Number of a specific type of device *dv* (two 120W heaters, five 180W heaters, a 2000rpm blower) used in the department
$(N_t)_w$	Number or quantity of workers in a category involved
N_{voj}	Variety of joints or number of different joint types
N_w	Number of the worker in the category associated with the quantity of product
$(N_w)_{ct}$	Number of workers in the category *ct* associated with the quantity of product
$N_{whd,}$ n_{whd}	Number of working hours per day
op	Operations 1,2,…N_{op} (disassembly, sorting, etc.) making up the PLET option
P	Product weight
P_{cf}	Product configuration
pcr	Performance rating
$(pcr_{pr})_{typ}$	Performance specification type(shelling efficiency,…) rating for the part
pcs_{pr}	Performance conformity score of the part or material
p_{dpm}	Desired profit margin
p_{isp}	Intended sales price of the reworked product
p_{iss}	Ideal safety standards
PLE	Product Lifecycle Extension
PLET	Product Lifecycle Extension Technique/Method/Process
PLETs	Product Lifecycle Extension Techniques/Methods/Processes
pr	Part/material type 1,2,..., N_{pr} required by the PLET for the product
$(pr_{eis})_{typ}$	Part or material's required ecological index type standard value
$(pr_{eiv})_{typ}$	Part or material's ecological index type(reusability, emission,…) value
PRICE	Programmed Review of Information for Costing and Evaluation model
p_{rqd}	Market required performance specification type *typ* for the product
p_{sp}	Standard performance specification type *typ* for the product
p_{srqdm}	Minimum value of specification type *typ* demanded by the market.
p_{rqdp}	Market required performance specification type *typ* for the product
$p_{rqdr,}$ pr_{srqdr}	Minimum value of specification (type) *typ* for the part or material needed for the product quality.
p_{sp}	Performance standard specification (type) *typ* of the part available on the market
p_{ssp}	Value of safety specification type *typ* for the PLET finished product

pr_{ssp}	Value of safety specification type *typ* for the part available on the market
p_{spp}	Standard performance specification type *typ* for the product
p_{spr}	Performance standard specification type *typ* for the part available on the market
p_{srqdm}	Minimum value of specification type *typ* for the product required by the market.
p_{ssp}	Value of safety specification type *typ* for the PLET finished product
p_{sub}	Average price of the substitute
$_{ptyp}$	Index types 1,2, …, N_{ptyp} (reusability, etc.) peculiar to legislative attribute
p_u	Utility type rate in DM/kWh or DM/litre or DM/min or DM/kg
q_{air}	Quantity of air consumed per period
q_{cptr}	Quantity of the product supplied by competitor
q_{dcm}	Estimated quantity of the product demanded
q_{MC}	Total quantity of materials consumed per unit reworked product
q_p	Quantity of product for which the utility type, *u*, is used
q_{pa}	Minimum quantity of components reuse or environmental performance standard type required by law
q_{pe}	Quantity of components reused or environmental performance standard type achieved
q_r	Quantity of the material type used per period
q_{pr}^{fr}	Subjective supply volume rating of part/material type *pr*
$(q_{pr})_{av}$	Quantity of part/material *pr* available
$(q_{pr})_{rqd}$	Quantity of part/material *pr* required
$(q_{su})_{pr}$	Quantity of part/material *pr* supplied
q_{rp}	The amount of the material type *r* required in the production of a unit virgin product
q_{rpp}	Quantity of the non-toxic material type 1,2,… N_r consumed per unit product
q_{rrmp}	Quantity of material type *r* reclaimed per unit reworked product
q_{rtd}	Quantity of retired product for the period under consideration
q_{rwd}	Number of product reworked by the process in the period, if job-order costing method is used (or equivalent unit of product reworked in the department for the period, if process costing method is used)
$\left(q_{suso}^{cu}\right)_{pr}$	Current quantity of material type *pr* supplied by supply source *suso*
$\left(q_{su}^{20y}\right)_{pr}$	The largest total quantity of part/material type *pr* supplied in 20years
$q(_{tmc})_{fp}$	Quantity of toxic materials needed for the production of a unit virgin product
$q(_{tmc})_{rwp}$	Quantity of toxic materials required for reprocessing a unit product
q_{txpp}	Toxic material content per product
q_u	Quantity of the utility type, *u*, used per period (in kW, litres, …)

$(q_{wcst})_{op}$	Quantity of the waste constituent type generated by the specific operation
q_{wst}	Quantity of solid waste generated by the process per period
q_{wtrc}	Volume of water consumed per period
r_{cdv}	Fuel type consumption rate in *Kg/s* by the device type
RECYCLEAN	Environmental information system and management manual
RELOOP	Reverse Logistics Chain Optimisation in a Multi-user Trading Environment
recmd	Reconditioning methods 1, 2, ..., N_{recmd} (twist, bend, blow, etc.)
ReStar	A design for disassembly software tool
resutyp	Resource type 1, 2, ..., $N_{resutyp}$ (personnel, water, energy, etc.) considered
R_{pf}	Performance requirement of reworked product
rrmp	Material types 1,2,…, N_{rrmp} (copper, zinc, etc.) reclaimed
R_v	Reassemblability
SAW	Simple Additive Weighting
scs_{pr}	Safety conformity score of the part or material
s_i	Site
sl	Sales
slt	Sales cost element 1,2,..., N_{slt}
srs_{pr}^{fr}	Fuzzy rating of the supply seasonality of material type *pr*
suso	Supply source 1, 2, ..., N_{suso}
t	Time
t_{actvy}	Actual time required to complete each activity constituting an operation
T_{af}	Level of resource type which meets the requirement of alternative j and is available in the region of the firm which the firm can afford to pay for
t_{APOT}	Actual process operations time
t_{AUXT}	Auxiliary times
T_{av}	Level of resource type which meets the requirement of alternative j and is available in the region of the firm for purchase
t_c	The delivery time requested by the customer in days
T_{cles}	Cleaning score
t_{CST}	Customer set time
T_{CXS}	Product complexity score
T_{dags}	Inspection and diagnosis score
t_{DET}	Delay time
$T_{dirinov}$	The degree of importance/relevance of the innovation/novelty type
T_{disrr}	Disassembly requirement rating
T_{diss}	Disassembly score
t_{dv}	Average time of device usage in the period (hrs, min, s as deemed fit)
t_{ec}	Estimated number of hours of the period of energy use

$(T_{efr})_{clmd}$	Efficiency of the cleaning method in cleaning the product parts
T_{eodrl}	Ease of liaison dissolution rating
T_{eods}	Ease of dissolution score
T_{eorr}	Ease of reassembly rating of the joint/part/fastener type jt $_{jt=1, 2,..., N}$
$(T_{efr})_{recmd}$	Effectiveness of the reconditioning method in correcting the fault of the part
$(T_{efr})_{somd}$	Effectiveness of the sorting method in separating the product parts
$(T_{efr})_{tesmd}$	Effectiveness of the test method in assessing the performance quality of the part/module/product
$tesmd$	Test methods 1, 2, ..., N_{tesmd} (tensile test, compressive test, etc.) utilised
tim	Sub-category of indirect material (product supportive material, liaisons, …)1,2,..., N_{tim}
$(T_{impr})_{clmd}$	Impact rating of the cleaning method
$(T_{imp})_{recmd}$	Impact rating of the reconditioning method(s) on the part and/or liaison
$(T_{imp})_{tesmd}$	Impact rating of the test method(s) on the part
$T_{inovrcp}$	Competitor´s product innovation type rating
$T_{inovrPLET}$	Product´s innovation/novelty type rating
t_{iwm}	Inspection of the work by measurement
t_m	Time duration in which the specific machine type m is involved in operation op in the period under consideration (i.e. number of minutes of its use in the month) minutes
t_{mop}	Time duration in which the machine type m is involved in the operation
t_{mt}	Time to mount tool
t_{mwp}	Time to mount work piece
t_{ptrw}	Portion of tool insert replacement time per workpiece
t_{raj}	Tool readjustment time
t_{rrw}	Replacement/repositioning of the workpiece
t_{rsp}	Tool resharpening time
TOPROCCO	Total Product Life-Cycle Cost Estimation
TOPSIS	Technique for Order Preference by Similarity to Ideal Solution
t_{orm}	Time to obtain raw materials from store
t_{ot}	Time to obtain tool from store
T_p	Level of resource type possessed by the firm
T_{pacr}	Packaging method rating
T_{PCXT}	Process characteristics
T_{PDCD}	Product condition score
T_{PDCF}	Product configuration
t_{PLET}	Estimated required time to carry out the PLET option
T_r	Level of resource type requirement by alternative j

T_{rec}	Reconditioning score of the PLET
T_{recrr}	Required reconditioning rating of parts and liaisons
t_{rt}	Time to return used tool
$(T_s)_{op}$	Individual operation's score
T_{sorts}	Sorting score
T_{TCAP}	Techno-capability of the facilities
$(T_{Thrr})_{op}$	The rating of required thoroughness of the PLET option's operation
T_{Thrs}	Thoroughness score of the PLET option
T_{reas}	Reassembly score
T_{rerr}	Reassembly requirement rating of the product
$T_{resrtyp}$	The suitability rating of the resource type
T_{resu}	Resource suitability score
T_{rurp}	Reusability rating of the joint/part/fastener jt jt =1, 2,..., N
t_{SUT}	Set-up time
tx_{WR}	Toxicity of waste
typ	Types of cost/item/parameters 1,2,..., N_{typ} relevant to the specific issue under consideration
t_w	Time duration in which the worker type worked on the PLET in hours
t_{wdy}	Work day (*hrs*)
u	Utility type 1,2,..., N_u
VADL	Value-added direct labour
v_{effl}	Volume of liquid effluents discharged per period
v_{gsem}	Volume of gases emitted per period
w	Categories of workers 1,2,..., N_w involved
$wcst$	Waste constituent type 1, 2, ..., N_{wcst}
w_{dv}	Energy consumption rate by the device/item in W or kW
wor	Workability rating of the material or part
wos_{pr}	Score of the workability (machinability, weldability,…)of the part or material type
$(w_s)_{ct}$	Average wages and salaries of workers in the category per period DM
w_w	Wage rate of the worker type involved in the PLET in DM/hour

List of Figures

List of Tables

1. Introduction and Goals definition

Product life extension refers to the elongation of the service life of a product. The need to extend the life of a product arise because a mechanical, electrical or electronic product is usually designed to be used for a certain number of years after which it will no longer be able to serve its purpose. At the end of this service life an ominous event, either a breakdown due to wear and tear or obsolescence, is expected to happen. At this point the product is to be discarded and a new one to be purchased. The inculcation of such consumerism habit of purchasing, using, discarding and repurchasing new product without the consideration of the environmental consequences came in the dawn of industrialisation. At that time, design and process planning decisions were directed towards improving product functionality, production rate and quality with little or no consideration of the environmental consequences. These resulted in the manufacture of unsustainable products that were discarded at will (Figure 1.1 on page 2 is an example). The resultant environmental disasters that arose towards the end of this century and the realisation by the populace that such enormous economic wastes cannot continue indefinitely necessitated a change in consumption habits. They also spurred various governmental and non-governmental actions to stem the tide of environmentally disastrous trends. Some of the governmental actions include the enactment of environmental control laws such as soil-, water-, and air-pollution control acts. Others are the establishment of organisations for the promotion of industrial sustainability, waste management and monitoring, as well as financing research in pollution prevention and control. Many companies, in recognition of the fact that taking a proactive approach is better than a reactive approach to environmental issues, have also launched “green projects” with the aim of reducing waste and manage their old products in environmental-friendly manner. Companies try to go this way by redesigning their products, and by retrieving their old products and reprocessing them.

As a result of the need for environmentally acceptable products, a lot of research efforts have been directed at optimal resource utilisation and reuse. However, the research efforts are concentrated on the design stage and on the disassembly aspect of the end-of-life stage. Although design- and disassembly-focused approaches are good but end-of-life stage consideration of products must go beyond disassembly if the opportunities abounding in the resource use optimisation are to be tapped fully. The far-reaching consideration of resource utilisation and reuse does not only involve the product retirement stage but also the utilisation stage, both stages constitute the product life extension domain. Figure 1.2

(on page 3) shows the various areas of research concentrations and the product life extension area, which is the focal point of this work.

1.1 Importance of Product Life Extension

Product life extension as a pollution prevention, resource conservation and consumer waste minimisation initiative has environmental, economic, and communal benefits. These benefits include the elimination or reduction of health hazards that could result in cancer, neurological disorders, and birth defects which can be traced to environmental exposure to manufacturing activities' released- and post-consumption wastes.

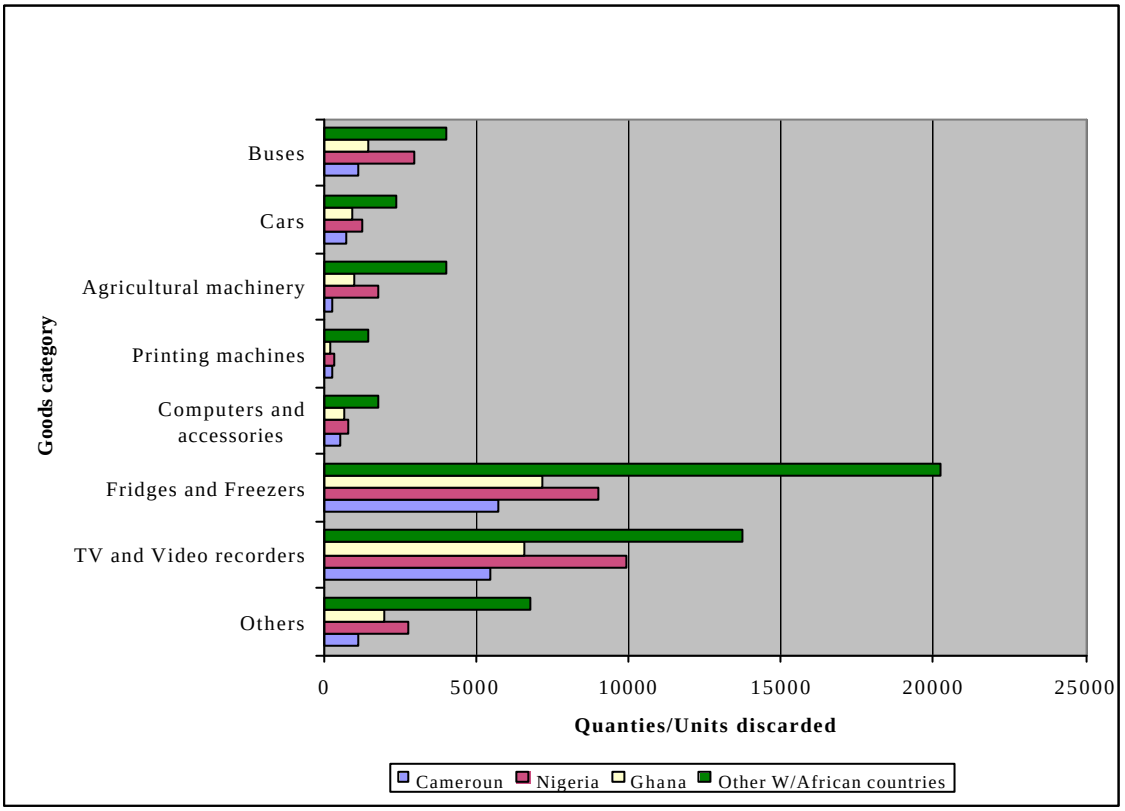


Figure 1.1: Estimated quantities of discarded durable goods in some African Countries in 1998/99 [DUNM 2000]

Moreover, extending the life of some products are economically essential because many of them are pre-environmental conscious campaign products (Figure 1.3, page 5) that have been manufactured before environment became an issue and are currently being used. Some others are transition products that were developed before the current campaign became widespread. Making significant design changes to some of these products to incorporate environmental consideration may not be easy because of high capital required

to change their manufacturing facilities. Similarly, many of these products at their utilisation cannot easily be replaced because they are high cost investment goods.

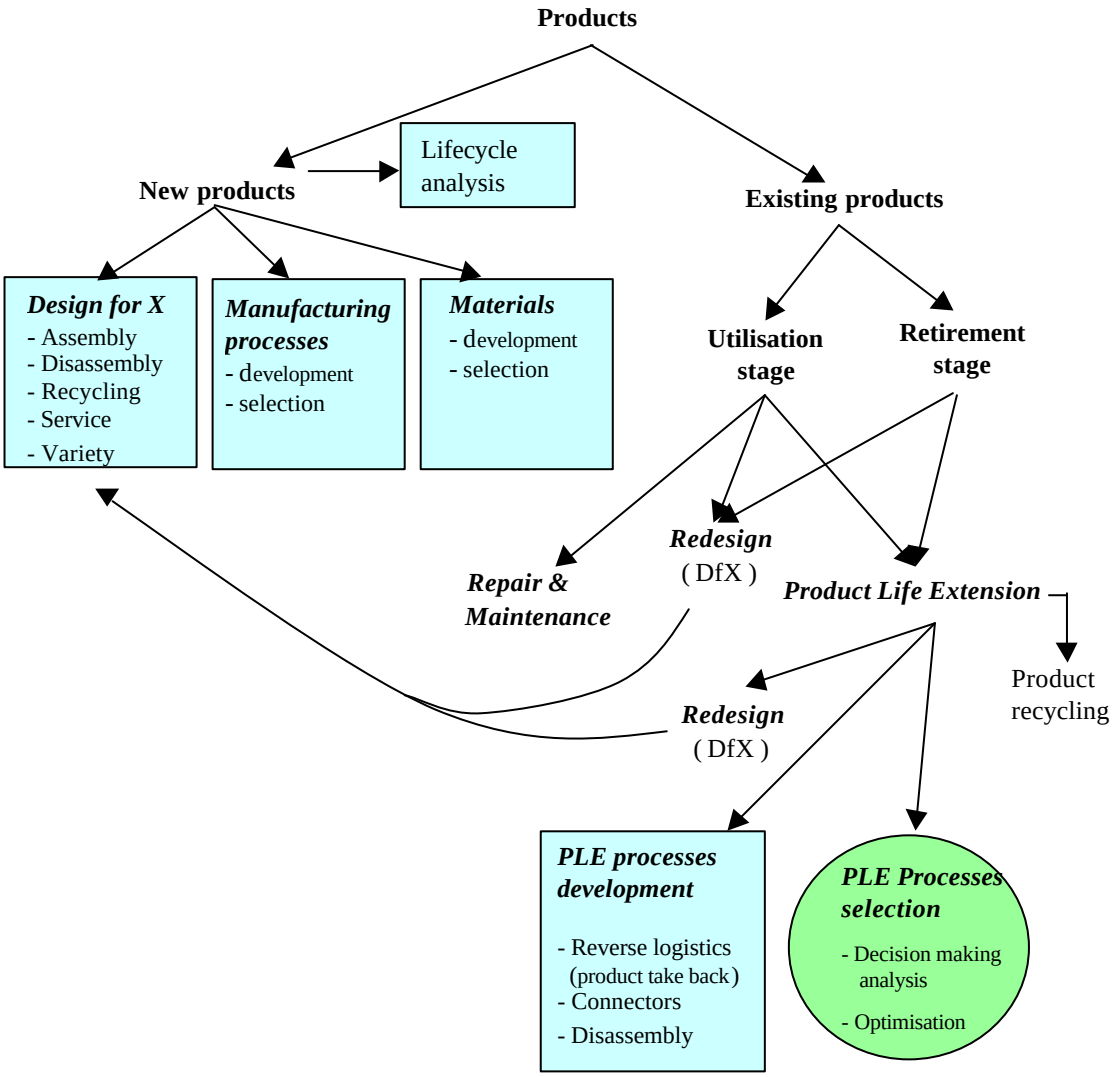


Figure 1.2: Eco-product related research

Furthermore, Table 1.1 (on page 4, for example) shows the average number and worth of some of these goods that are expected to reach retirement stage within the next five years. The economic value of these products to those concerned warrants life extension considerations. Baas and Warner [BAWA 93] reported that electro-mechanical and mechanical devices nearing the end of their service life can have their life times extended by 10-20 years and their overall performance improved by upgrading them. It was also found out that lower costs and shorter lead times are incurred by upgrading than by replacing. The life extension studies performed so far also supported the concept that the

cost of extending the lifecycle of a mature unit is significantly less than that of a new unit for return on investment and that the modernisation option can provide increased output, efficiency, and availability. The lifecycle of these products can thus be extended to optimise their utilisation. The newly developed products, which are designed for multi-lifecycles, are even more suitable for lifecycle extension because of their attributes such as modularity, connectors' dissolubility, component durability and reusability [ANON 84, BAWA 93, OECD 82].

Types of durable goods	**Quantities of each category of goods according to countries**				**Total worth in thousand DM**
	Cameroon	Nigeria	Ghana	Other W/African countries	
Cars	2500	4200	3000	8000	57,525
Buses	3800	10000	5000	13500	339,150
TV and Video recorders	10000	18000	12000	25000	7,150
Fridges and Freezers	12750	20000	16000	45000	13,500
Computers and accessories	850	1300	1100	3000	9,375
Printing machines	500	700	480	3000	20,217.6
Agricultural machinery	300	1800	1000	4000	84,490
Others	1400	3500	2500	8500	47,700

Table 1.1: Estimated number and worth of some of durable/investment goods that will reach retirement stage within the next five years in some African countries [DUNM 2000]

In addition, there are a number of factors illustrated in Figure 1.4 (on page 8) that are favourable to product life extension. These include growing public opinion against products that takes heavy toll on the environment and the increasing demand for environmental friendly goods. Executing product life extension policies therefore enhances the goodwill of the firm. Such good corporate image resulting from "greening" the product can give the firm a market advantage over its less "environmental-mindful" competitors. It also saves the firm some costs such as landfill cost and remediation cost. Sections of some environmental acts encourage firms by providing incentives such as tax relief for certain firms that embark on green project. Increasingly tightened environmental control on trans-national goods also makes "greening" mandatory for firms whose appreciable sales come from exportation of their goods. Furthermore, the development of new technologies with lower resource consumption and reduced waste generation is a boost to product life extension. New low-cost materials that are non-toxic are also becoming available for use, and to replace toxic and more expensive materials that were previously used. Reduced raw

material consumption, reduced water and energy costs, reduced waste storage space, reduced waste handling time and costs, as well as reduced use of expensive end of pipe technology are other financial benefits accruing from product life extension [GUPR 86, GRJE 86, OECD 82, JACK 93, INDE 98, DIGI 98].

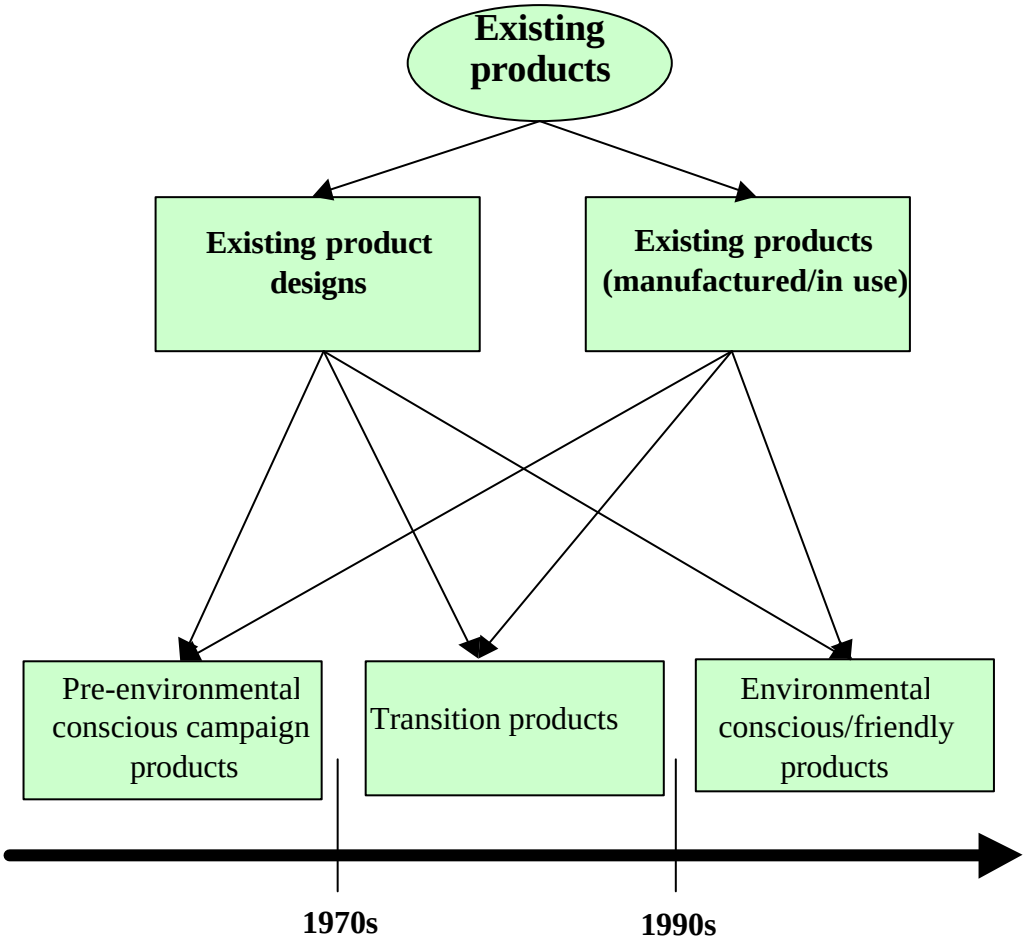


Figure 1.3: Existing products classifications

1.2 Product Lifecycle Extension Problems

As impressive as extending the lifecycle of a product is, it faces a number of problems. Some of the issues constituting problems to product life extension are:

- **Usage of complex materials**

Material selections were formerly based on cost and functionality. Their durability is lightly considered. Their environmental impact and reusability were also considered inconsequential. Similarly, many of the newly developed materials are complex such that their separation at the end of product life is economically infeasible and their disposal is

environmentally degrading. Such materials have to be substituted, because the material of a product whose life is to be extended has to be durable and environmental friendly.

- **Usage of indissoluble connectors**

Disassembly is a very important operation in resource reuse. For economically sound product life extension, the removal of the liaisons and dissolution of the joints should be very easy and fast. However, many of the connectors used can only be loosened by destructive disassembly and the majority of those dissoluble ones can only be manually disassembled. This makes the productivity and economic benefit of the process to be low. To facilitate profitable product life extension, quick 'disassemblable' connectors have to be developed and incorporated into product design.

- **Lack of adequate data**

There is a need for adequate data to test for availability of markets for the purchase of required parts and materials, as well as determining the size of demand for products whose life has been extended. This is essential for planning purpose and to assure the investors of the possibility of suitable return on their investment. The accuracy of some of the available data is also in doubt, particularly in many developing economies where adequate records are not kept. This also poses problem in making excellent plan for product recovery particularly the pre-treatment logistics aspect.

- **Discouraging industrial culture**

Although industrialism intends to satisfy needs and improve efficiency, it has been plagued by culture of waste. This arose from planned obsolescence based product design and manufacture. The ever-increasing shortness in time period between significant changes in product designs also makes long time planning for lifecycle extension difficult. As an essential part of creating a sustainable industrial culture, new products development must be based on assessment of the environmental impacts in all phases of the products' lifecycles and also on extendibility of the useful life of the products. This will result in less frequent product replacement which in turn means less waste and less use of energy and material resources [SHIR 99, ALTI 99].

- **Quality assurance problem**

The inability to exactly determine the extent of deterioration in retired product condition makes quality assurance of reworked product difficult. The variation in the degree of deterioration in retired product condition stems from the following: differences in the product handling/use, differences in sourcing, differences in corrosivity of the environment where they were used, susceptibility of the materials composition to wear and tear, and design changes. Some materials are exposed to certain environmental conditions such as ultra violet radiation during their use, which may substantially deteriorate their material value. All these make it impossible to estimate the techno-economic life of a reworked product.

- **Lack of suitable infrastructures**

A number of facilities are needed for efficient product life extension management, among these are good product take back network, and framework for monitoring product take-back, lifecycle extension consequences and improvements. All stakeholders should know where each type of product should be returned and whether there will be charge or compensation for returning the product. It should also be clear whether the return/collection will be to/from a central depot or collection centres. Product life extension information collection and data processing facilities are also essential for determining the appropriate "enviro-technoeconomic" product life extension possibility for each class of product under set of conditions. However, these are either not available or are inadequate in some countries.

The severity of these problems and other problems highlighted by Stahel and Jackson in [STJA 93] are location dependent. The locational difference makes it pertinent to evaluate various life extension opportunities and to systematically choose the best out of the product life extension processes that can be used to meet the desired goals. From the on-going, it becomes necessary to have a comprehensive decision making methodology that can be employed under various locational conditions. It falls within the province of this methodology to evaluate various opportunities abounding in the optimisation of the product service life and recommend the best process to adopt for achieving the desired goals.

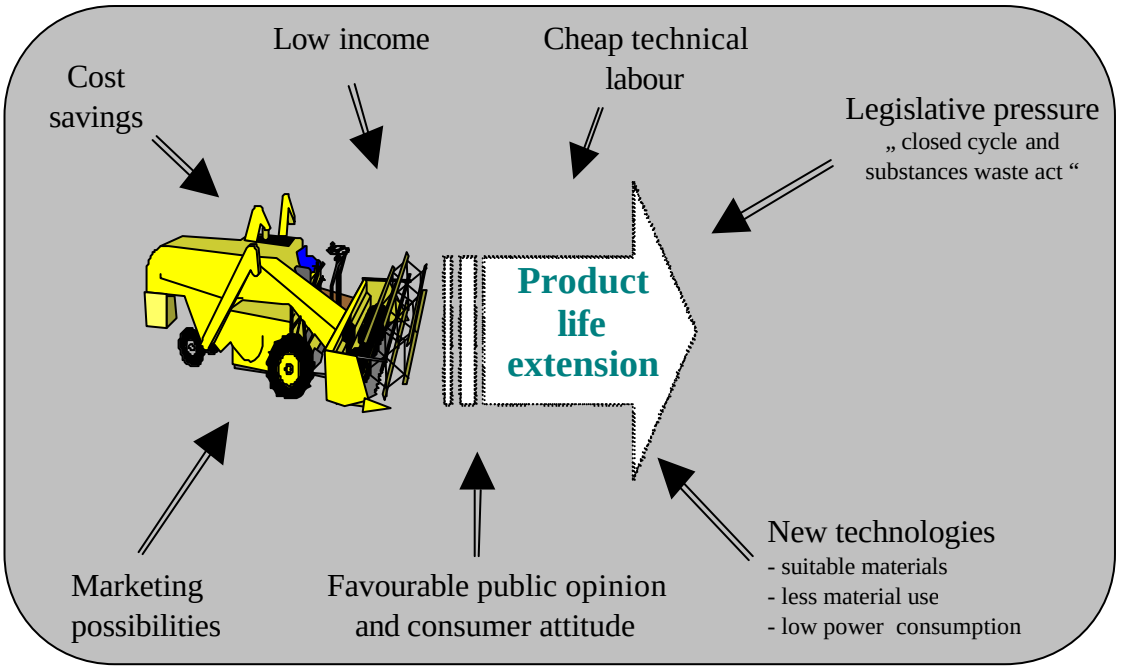


Figure 1.4: Factors in favour of product life extension

1.3 Research objectives

The main goal of this work, therefore, is to develop a systematic decision making model that integrates environmental, economic, technical, market and legislative factors into product life extension process selection, that will yield an optimal process (Figure 1.5 on page 9). This is to be accompanied by a demonstrative computer implementation tool that will serve as user-computer interface for the real life application of the decision model. Furthermore, the sensitivity of the decision outcome to changes in data and importance of some factors are to be examined. Finally, the model validity is to be tested with a case study on an agro-mechanical product. Figure 1.6 (page 10) shows the summary of the capabilities and the build-up of the decision model. Details on each of them will be found in the later chapters.

1.4 Dissertation layout

The arrangement of the dissertation is illustrated by Figure 1.7 (on page 11). This chapter gives the background information on product life extension, its importance and its problems. It also highlighted the need for a comprehensive decision making methodology, which can be used to choose the best out of the feasible product life extension processes. It further shows the scope of the work done and the contributions made by this research work

to decision making in product life extension domain. The second chapter focuses on the approach used in developing the decision model. The proposed product life extension process selection (PLETS) methodology and the accompanying computer implementation prototype will be discussed in chapter three. The discussion on the case study used to test the model will be found in chapter four while the results and discussion on the results of the tests will be found in chapter five. Conclusions and recommendations on the outcome of the work are given in chapter six. It is followed by summary and the thesis ended with appendices.

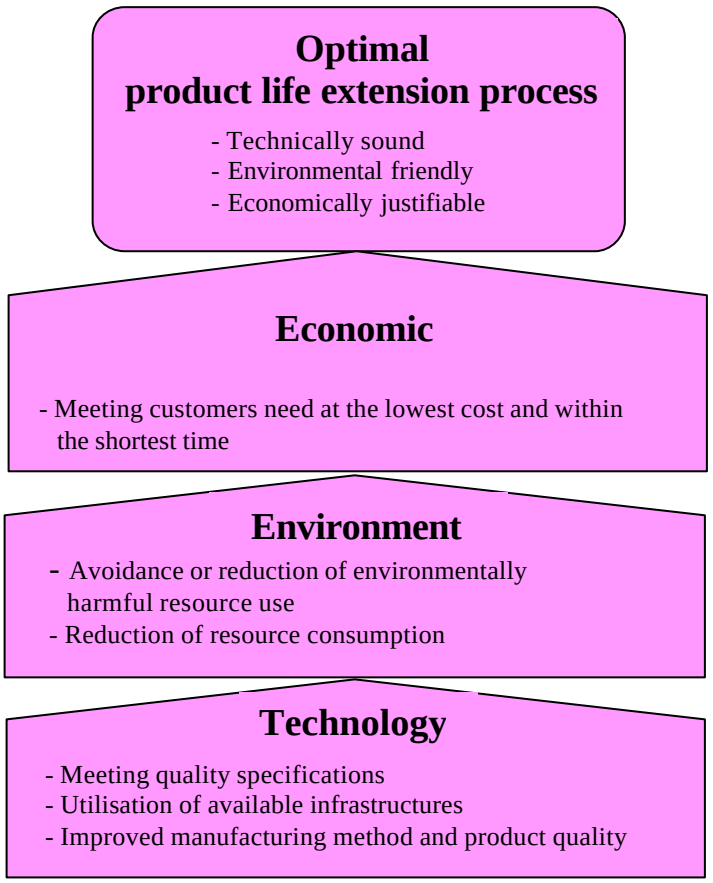


Figure 1.5: Illustrated goals of the product life extension process selection model

CONTRIBUTIONS MADE BY THIS WORK

- Development of an evaluation/ decision making framework for:
  - Assessing product life extendibility, reworked product marketability, facilities' suitability for product life extension, product life extension cost, and legislative conformity
  - Product life extension processes (PLET) selection:
    - Establishment of attributes, sub-attributes, and sub-sub-attributes for PLET selection
    - Development of indices in tabular form for PLET evaluation
    - Development of mathematical correlations for PLET evaluation involving the hybridisation of:
      * Multiple Attribute Decision Making (MADM) methods:
        + Simple Additive Weighting (SAW) method and
        + Conjunctive method with
      * Distributive or mixed value function
- Development of a prototype / demonstrative application interface
  - User-computer interaction module (INFOCOL)
  - Mathematical correlations implementation module (INFOPRO)
  - Results display module (INFORES)
- Development of minimum standards on each attribute used for PLET selection
- Validation of the methodology and the computer implementation application with a case study

Figure 1.6: Capability and the build-up of the decision model

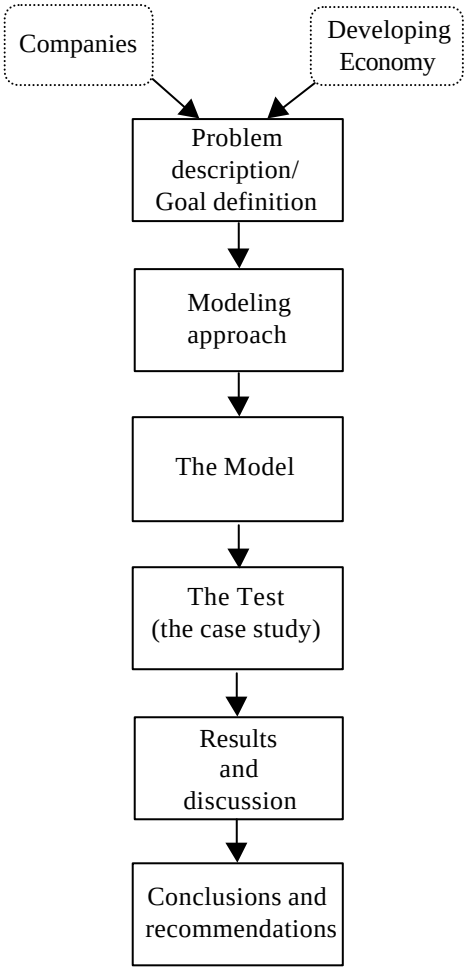


Figure 1.7: Illustration of the dissertation arrangement

2 Approach to the Model Development

The product life extension decision problem highlighted in chapter 1 can only be adequately solved by using an appropriate decision making method. But, there is a large number of decision-making methods mentioned in the literatures [HWYO 81, CHTH 84, HACH 84, ZIMM 90, CHHW 92, CHRY 92, STSP 92, SPBU 94,VEER 94, BRHE 95, SUCA 92]. The availability of a wide variety of approaches (Figures 2.1 and 2.2 on pages 15 and 16) poses another problem of choosing a suitable method. According to Hobbs [HOBB 84], these decision-making methods differ widely in the purposes they serve, their ease of use and theoretical soundness, and the evaluations they yield. An intending user must thus consider the appropriateness of the method to the problem in terms of the value judgements it asks from the decision maker, the types of alternatives it can consider, and the forms of evaluations it yields. Furthermore, the decision maker must also consider how much effort and knowledge the method requires. The theoretical validity of the method in terms of the effectiveness of the model solution should also be determined. Moreover, the results of the method have to be compared with other methods to determine how much they differ from the results obtained from proven methods. Careful evaluation of these methods may necessitate modifications and/or combination of methods in a form that is appropriate for a specific application [HOBB 84, ZIMM 90, CHRY 92, VEER 94, CHNA 94, BRHE 95]. A study of the works of Overby, Stahel and Johnson, Bras and McIntosh, and Allenby and Richards [OVER 79, STJA 93, BRMC 99 and ALRI 94] shows that decision-making in product life extension domain requires multicriteria consideration. Furthermore, the small, explicit number of alternative processes available to choose from reveals that the suitable method has to involve a multiple attribute decision-making model [HACH 84; HWYO 81, LAHW 94].

Although there has being some models developed for the evaluation of end-of-life options, they are either single criterion- or bicriteria-based. Some of these works include those of Chen and associates, Cramer and associates, and Low et al [CNCP 93; BRMC 99; LOWD 96; LOWD 97]. Other works which focused on only some aspects or on one or two product life extension processes include the works of Bras and associates, and Shu and associates, [BRMC 99, SHFL 95]. The work of Chen and associates assesses the economics of product design for recyclability by using cost and benefit analysis method. By this method, the cost of each end-of-life option was first computed, followed by the calculation of the benefits of each of the options. The results of the cost and benefits calculations of

each of the options are compared to determine the most profitable alternative. However, the focus of the work is on the product design with the consideration of the end-of-life stage alone, excluding the utilisation stage. Furthermore, the end-of-life options considered are Parts reuse/sale, product recycling, shredding, and incineration/ landfilling while the basis of evaluation is limited to environmental and economic factors.

Low and associates presented a number of mathematical models to assist designers in evaluating a number of end-of- life options of a product at the conception stage of the product development. The options being considered are recycling, remanufacturing, resale, upgrading and disposal. The cost models evaluate the cost of each model as a fraction of the manufacturing cost and consequently evaluate the trade-off between the options. Again the basis of evaluation is only financial and is directed at the product design.

Moreover, Bras and McIntosh [BRMC 99] have also reported a number of works on remanufacturing and disassembly. Among them is the development of metrics for the assessment of remanufacturability of designs and for measuring ease of assembly, disassembly, testing, inspection, cleaning and part replacement by Bras and associates. A large number of environmental tools have also been developed within these last two decades. Those with some relevance to product life extension include AMETIDE, BDI Range, GE Manual, LASeR, PRICE, RECYCLEAN, and ReStar. Summaries of the purposes and limitations of these tools are shown in Table 2.1 on page 17. [DEED 99, ECOD 99, BOBU 98 and ISLE 95] should be consulted for detailed information on these and other related tools.

2.1 Choice of screening and evaluation methods

In order to meet the unsatisfied need for flexible comprehensive decision model that can be used for PLETs' screening, evaluation, prioritisation and selection, the steps recommended by Hwang and Yoon [HWYO 81] (Figure 2.3 on page 18) is used in conjunction with Figure 2.2 (on page 16) to select the MADM models on which the proposed model is based. From these figures, one can see that Simple Additive Weighting Method (SAW), Hierarchical Additive Weighting Method, ELECTRE and TOPSIS are suitable for evaluation, prioritisation and selection while dominance method, conjunctive method and disjunctive method are suitable for screening. SAW is preferred to all other evaluation methods because it has been successfully used for many real world applications and is

simple to understand. Similarly, the conjunctive method is used because it is the suitable method for screening alternatives that do not meet the minimum standard on attributes.

- **Simple additive weighting method**

According to Chakong and Hwang [CHHW 92], this method computes the overall score of an alternative as the sum of the weighted attribute values. The alternative with the highest score is selected. Mathematically, the alternative a_k to be selected is:

$$a_k = \left\{ a_i \left| \max \sum_{j=1}^{N_j} w_j x_{ij} \middle/ \sum_{j=1}^{N_j} w_j \right. \right\} \tag{2.1}$$

where x_{ij} is the outcome of the i^{th} alternative about the j^{th} attribute with a numerically comparable scale and w_j is the importance weight of the j^{th} attribute.

- **Conjunctive method**

The basic principle of this method is that the minimal acceptable levels for each attribute are used to screen out unacceptable alternatives. The decision maker specifies a minimal acceptable level or cut-off score for each attribute and check each alternative in turn to see which of them has the value of each of its attributes equals or exceeding the minimal acceptable level. An alternative a_i is an acceptable alternative if:

$$x_{ij} \geq x_j^{\circ}, j = 1,2,...,n. \tag{2.2}$$

where x_j° is a minimal acceptable level of x_j

This method is also applicable when the solution aimed at is to screen out unacceptable options. It is simple, easy to use and understand. However, its drawback is that an alternative with just one unacceptable attribute will be rejected even if it has high values for all other attributes [CHHW 92].

- **Choice of normalisation approach**

Normalisation, also called single dimensioning, of decision attribute values is required when using any one of the methods like SAW, Maximin and ELECTRE because of the expected presence of different units in the decision matrix. It is carried out to achieve comparable scales. Vector normalisation and linear scale transformation are the two commonly used normalisation approaches. Although any of the two methods can be used, the later is preferred for its simplicity. The adaptation of the later to PLET selection is such that when either the minimum value or maximum value equals zero, 0.000001 is used to ensure practicality of result. Furthermore, except under cost attribute, all scores used to calculate higher attribute hierarchy level score from sub-sub-attribute levels are normalized scores. [HWYO 81, SUCA 92] should be consulted for further details on both methods.

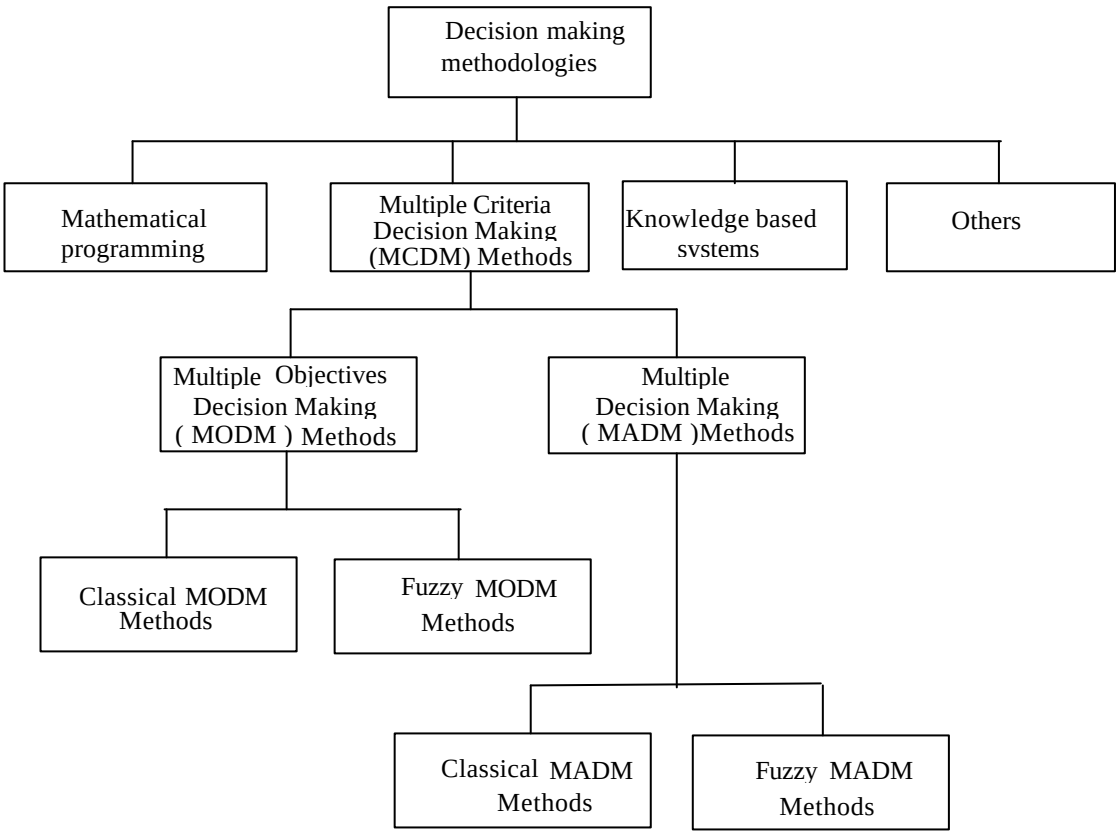


Figure 2.1: Some of the major classes of Decision Making Methods [HWYO 81, CHHW 92, CHRY 92,VEER 94]

Based on the guidelines given by Sanchez, Priest and Burnell [SPBU 94] on multiple attribute decision analysis structure, the following model development procedure (illustrated with Figure 2.4 on page 19) is followed: Goal definition, identification and analysis of PLET selection criteria, weighting evaluation criteria, minimum standard on attributes,

alternative identification and assessment, sensitivity analysis, and alternative selection. The product life extension problems and the goals of the decision model have already been discussed in chapter 1.

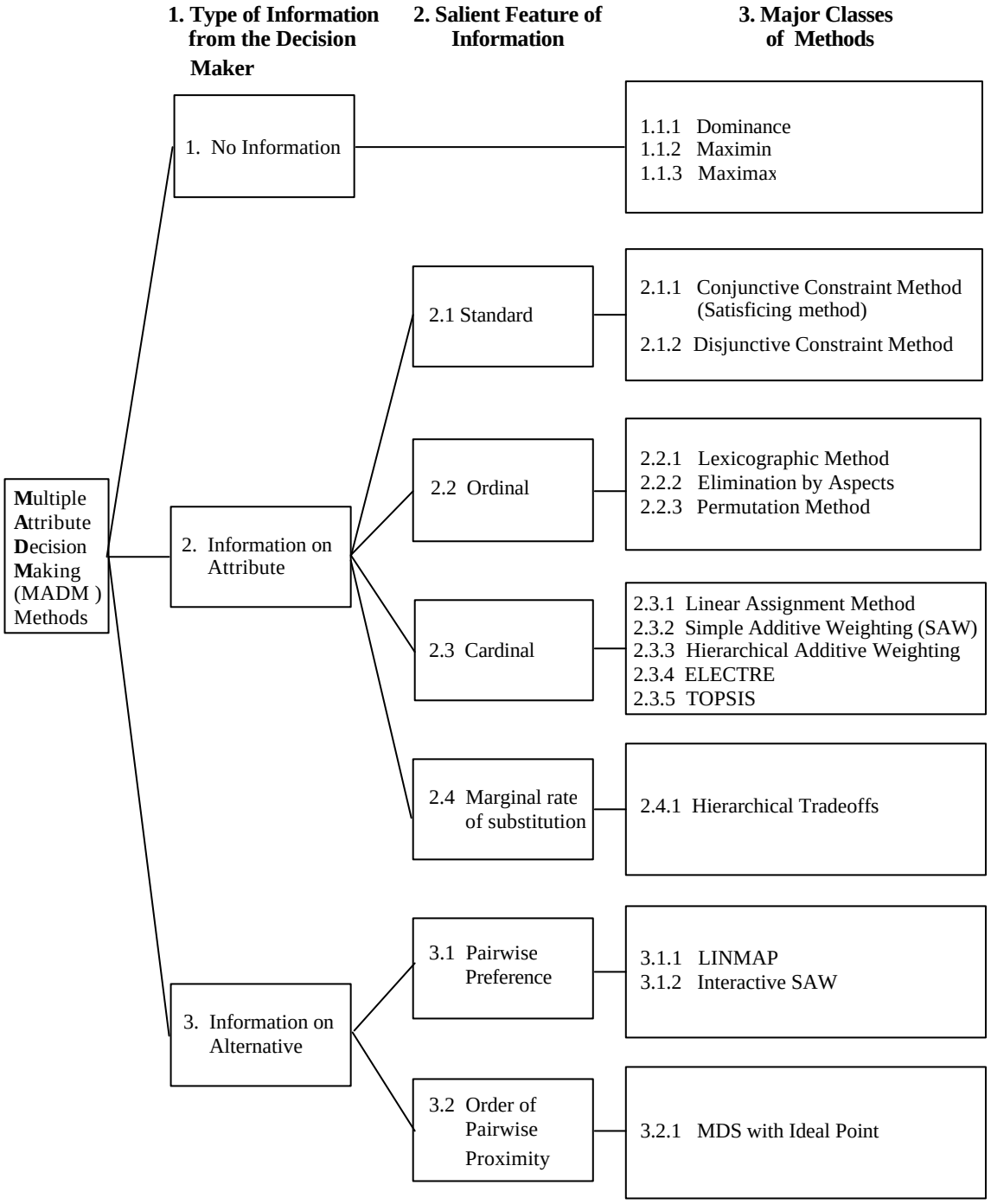


Figure 2.2: A taxonomy of methods for multiple attribute decision making [HWYO 81]

	Software	Purpose	Point of application in the product lifecycle	Limitations
1	AMETIDE	To choose a certain method of fastening and/or disassembly with an estimated time necessary to disassemble	Design stage	The focus is limited to disassembly.
2	BDI Range	To provide designers with estimations of assembly times, servicing time, assembly costs and redesign suggestions. It also has interactive databases to allow adjustment of processes to specific environments	Design stage	It is not meant for product recovery process selection
3	EDIT	To evaluate material recovery options in terms of cost and environmental distress	Unknown	The criteria for evaluation are not comprehensive enough
4	GE Plastics	To demonstrate possible uses and applications that allow easy recycling of numerous types of plastics	Unspecified	It is limited in applic-ability to plastics only
5	LASeR	To evaluate the servicability, recyclability and assembly of mechanical designs	Design stage	The analysis is based on costs, requires the insertion of extensive amount of information and focuses on design
6	PRICE	To estimate cost in all phases of hardware acquisition	Unknown	The software is limited to cost estimation
7	Recycling graph	To evaluate a design solution with regard to recycling and disassembly conformity	Design stage	The focus is the product design and not process evaluation
8	ReStar	To calculate and optimise expenses for the disassembly of a product, in order to find the optimal economical and environmental solution for the disposal / recycling of a product	Design stage	It is limited to cost and environmental impact evaluation
9	RELOOP	To optimise costs and environmental impact of Take-Back Logistics	Unspecified but it is likely to be at retirement stage	Resource recovery goes beyond take-back logistics only. Sensible decision-making in resource recovery requires more than cost and ecological factors.
9	Reverse Fishbone Diagram	For advance planning of disassembly and reprocessing sequence of a product at the end of its useful life.	Design stage	The focus is not on process selection.
10	TOPROCO	For product lifecycle cost estimation	The whole product lifecycle	It is limited to cost estimation only

Table 2.1: Some of the product retirement related tools and their limitations [DEED 99, ECOD 99, BOBU 98 and ISLE 95]

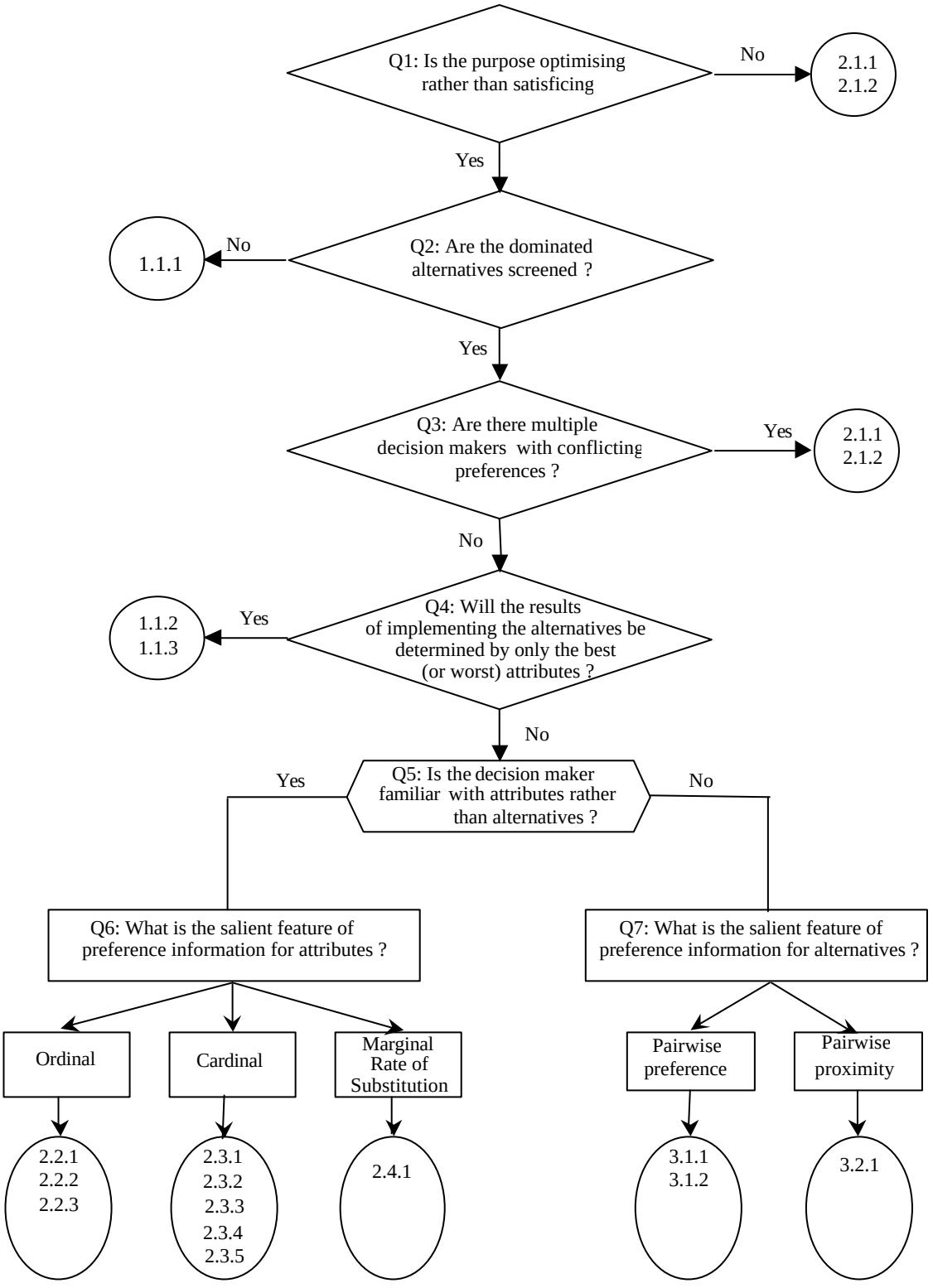


Figure 2.3: MADM method specification chart [HWYO 81]

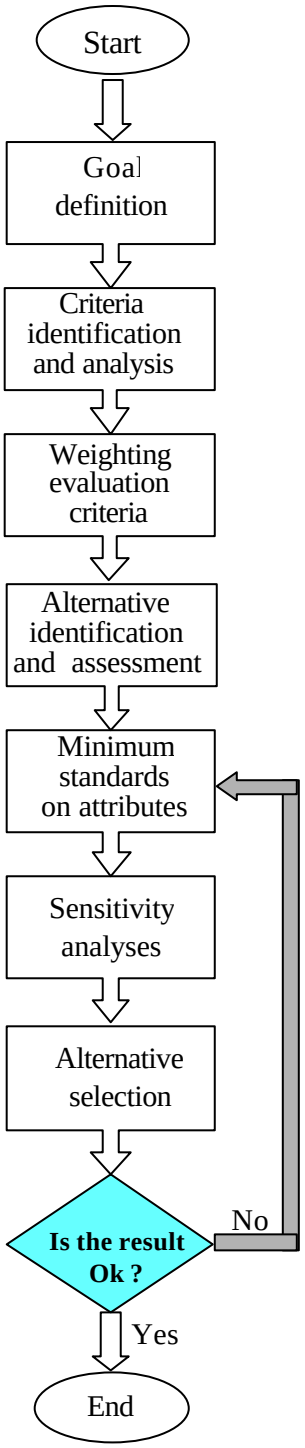


Figure 2.4: Product life extension process selection model development process

2.2 Identification and analysis of PLET selection criteria

Evaluation attributes or criteria are management and engineering measures used to evaluate the relative worth of each process alternative in terms of the extent to which they can be used to achieve product life extension goals. According to Sanchez, Priest and Burnell, and Sullivan and Canada, each of these criteria must be quantifiable and relevant to achieving a

pre-established goal. The relevance of the criteria depends on the management policies and the process environment. The validity of a selected attribute is assessed based on its contribution to a goal, the possibility of being measured or estimated with reasonable effort, and its capability of being used to differentiate solutions without bias between alternative processes [SPBU 94, SUCA 92]. On the basis of the aforementioned requirements in the criteria selection, Figures 2.5 – 2.9 show the attributes, sub-attributes and sub-sub-attributes considered essential for product-life-extension processes evaluation. The collation of these attributes is based on intuition and experience of the author as well as on the works of Siegwart and Senti; Steinhilper and Hudelmaier; Stahel and Jackson; Johnson and Wang, and Spicer and Johnson [SISE 95, STHU 93, STJA 93, JOWA 95, SPJO 98]. Furthermore, all the tables for rating the processes with regard to individual parameters are prepared based on the principles highlighted in [HWYO 81, CHHW 92] for quantifying the fuzzy attributes.

Although the repair and maintenance of high investment machines have been around for some time, the product take-back and asset recovery aspect of product life extension are still relatively new and growing areas of industry. A number of issues are yet to be cleared. Many companies producing durable goods (such as electronics) are considering the advantages and disadvantages of asset recovery and product reuse. Individual and corporate users are also assessing the benefits and modalities for extending the useful life of their asset. The motivations behind product life extension can be grouped into three, namely: profitability, legislation and environment. The fourth factor, which is technical attribute, is a necessity particularly in a developing economy where some of the resources necessary for product life extension may be lacking.

With regard to profitability, it is generally known that a good maintenance of high investment goods reduces their breakdowns and elongates the useful service life of the asset at a cost that is lower than purchasing new ones. Also, when durable goods reach the end of their useful life there are still many components within the product that have value. The recovery of this value represents a source of profit for the stakeholder. However, the stakeholder needs to assess the availability of parts and materials for resuscitating the products and the availability of demand for the renovated products in order to determine the scale of operation. The company also needs to find out the price that the buyer is ready to pay, and compare it with the cost of extending the life of the product. Furthermore, the qualities of the available parts and materials for the product resuscitation have to be

assessed in terms of their being able to meet the buyers demand for renovated product qualities. The company needs to also evaluate the type of the buyers in order to determine his mode of operation: whether to produce-for-open-market-sale, custom-production, or servicing-for-user. This will enable the company plan how to meet the delivery time. This profitability factor is thus categorised into three attributes: cost, market and time.

2.2.1 Cost attribute

Cost is considered as one of the most important issues in selecting an economically sound product-life-extension process. There is a wide variety of cost estimating methodologies. The particular method chosen depend on: the particular situation being studied and estimated; the reliability of the cost estimates resulting from the method, the cost of using the method and the time cycle required to carry out the cost estimation by using the method. Notable ones among these tools and methodologies include the parametric estimating, job-order costing, process costing, total cost of ownership, and total cost assessment [PCEI 99, TEIN 97]. A number of these methods are adaptations of the conventional accounting methods to specific situations to ensure accurate cost estimation [ANWA 94, BELK 91, BORN 92, FONG 98, RIGG 94, TANN 96]. After a careful study of these methods and their reported applications, particularly in the area of environmental cost accounting, hybridisation of cost estimation relationships (CERs) aspect of parametric estimating methods and total cost assessment (TCA) method with a lead for process costing adaptation was considered the most appropriate for PLET costing.

CERs are mathematical expressions of varying degrees of complexity expressing cost as a function of one or more cost driving variables. This technique uses validated relationships between a project's known technical and cost characteristics, and known historical resources consumed during the development, manufacture, and/or modification of an end item. It was reported that this technique facilitated rapid development of more reliable estimates while establishing a sound basis for estimating and negotiation. Its wide applications have been reported by US department of defence. Furthermore, by using the method, the department reported proposal preparation, evaluation, and negotiation cost savings of up to 80 percent; and reduced cycle time of up to 80 percent [PCEI 99].

TCA is a cost and project evaluation tool developed in 1997 by Tellus institute in Boston, USA. Its major difference from the conventional cost accounting methods being that it approached cost estimation in a different and more comprehensive way. Its wide acceptance

for costing pollution prevention options is exemplified by supports it enjoyed from USEPA and Canadian ministry of environment [TEIN 97, USEP 2000, CMEL 2000].

Product life extension process costs depend on the number of retired products reworked q_{rwd}, retired product condition T_{PDCD}, performance requirement of reworked product R_{pf}, product configuration P_{cf}, and unit cost of each cost element. The extent of product deterioration in the form of rust, wear, and fracture among others determines how much work that has to be done on the retired product as well as the amount of resources that is needed to bring the product to required performance level. Retired product configuration in terms of variety of materials used, variety of connectors used as well as the degree of complexity of its geometric make-up affect the ease with which individual operations making up the process can be carried out in restoring the product. These factors consequently affect time and eventually affect the labour cost as well as the delivery time. The product life extension process cost elements can be broadly categorised as material cost, labour cost and overhead. The detail of this categorisation is shown in Figure 2.5 on page 23. Cost category value per unit product reworked can thus be calculated from the expression:

$$c_c = \frac{C_i}{q_{rwd}} \tag{2.3}$$

where c_c Cost category value per unit product

C_i Total cost category incurred in the period under consideration

q_{rwd} Number of product reworked by the process in the period, if job-order costing method is used (or equivalent unit of product reworked in the department for the period, if process costing method is used)

Having known that each cost category in individual department for the period under consideration have to be divided by the number of products handled by the department, as highlighted in equation 2.3, each cost category value and their sum can be obtained as follows:

$$\begin{aligned} C_{PLET} &= f\,(T_{PDCD}, R_{pf}, P_{cf}, C_i, P_{qt}) \\ &= C_{DRT} + C_{OVH} \\ C_{DRT} &= C_{DM} + C_{DL} \\ C_{OVH} &= C_{FO} + C_{ASO} \end{aligned} \tag{2.4}$$

where C_{PLET} Process cost per unit reworked product

C_{DRT} Direct costs

C_{OVH} Overhead cost

C_{DM} Direct material cost

C_{DL} Direct labour cost

C_{FO} Factory overhead

C_{ASO} Administrative and selling overhead

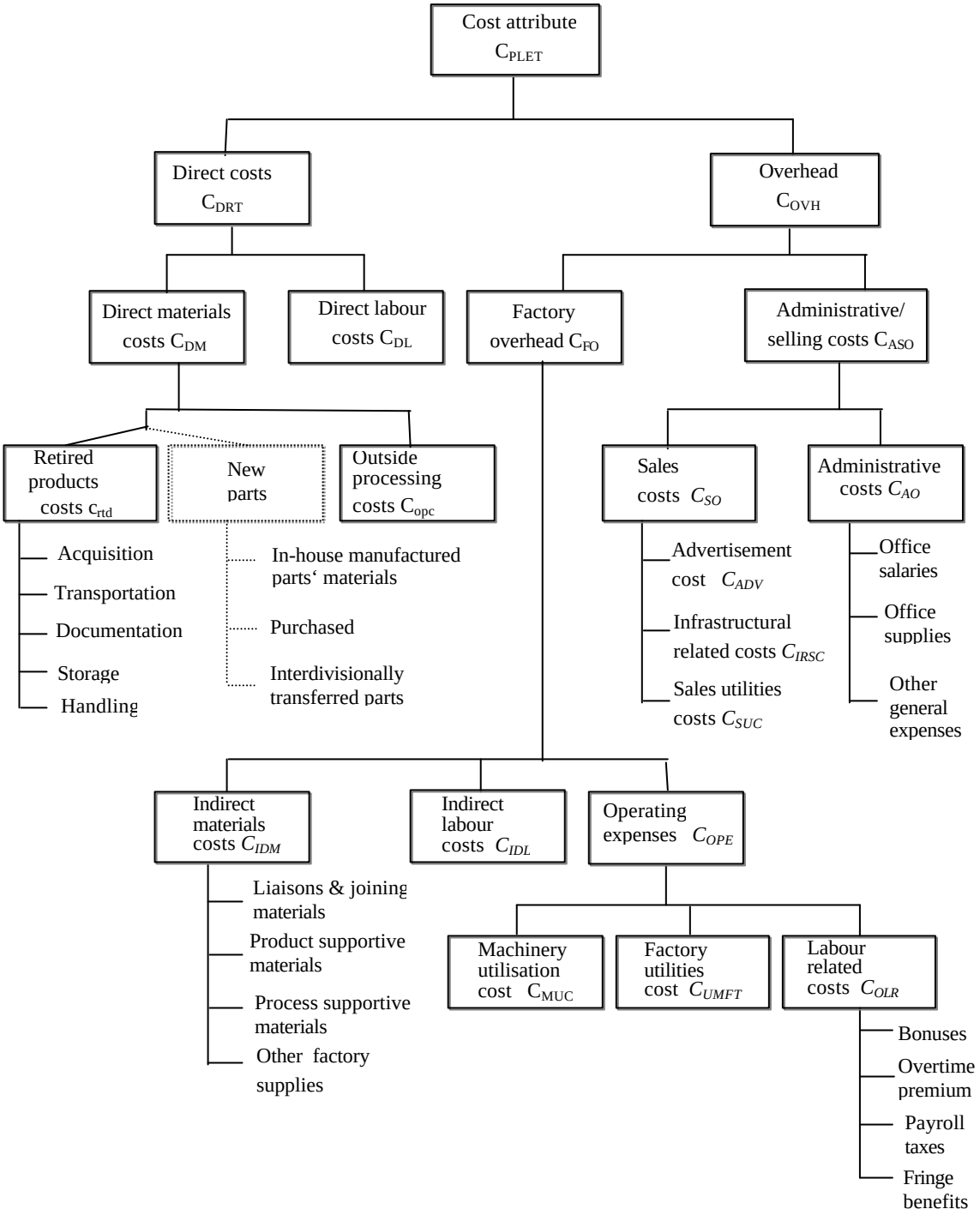


Figure 2.5: Elements of product life extension process cost

2.1.1.1 Material costs

Items referred to as materials vary from one company to another. But they generally include raw materials, purchased parts, subcontracted or interdivisionally transferred parts, subassemblies and assemblies. In this case, material costs consist of the costs of all material and parts used in the process of extending the life of a product. The costs can be divided into two sub-groups, namely: direct materials and indirect materials.

Direct material costs C_{DM} refer to quantity of materials that can be identified with the production of a specific product, be easily and economically traced to that product, and whose cost represents a significant part of the total product cost [ANCL 91, BELK 91, ARHE 95]. Thus, in this work, retired product is basically regarded as the direct material. Product take-back is aimed at recovering assets and resources, generate revenue, and ensure responsible end-of-life disposition. This take back programme requires a number of steps involving gathering, transporting, documenting, storage and handling. The retired product otherwise referred to as taken-back product is a product whose life is to be extended. It makes up at least 50% of the final product. This cost can either be simply estimated or comprehensively determined from the constituent sub-cost elements. The acquisition cost is the average cost of taking back or purchasing the used product from the consumer at the end of the product life during the particular time period. This is different from new parts purchases. Purchased (new) parts are seen in this work as being without defect, while retired products are defective. Also, retired product forms the bulk of the final product while purchased parts are only small fraction of the final product.

The transportation costs consist of the cost of transporting virgin materials, purchased parts and gathered products from collection centres to the factory. The transportation means used and their costs depend on methods availability, product fragility and these consequently affect the transport cost. Documentation cost is the cost of taking the materials and parts data before manufacturing, and retired product data before and after rework. The retired product data taken before rework are those relating to the assessment of the product condition at reception while those taken after rework gives the product condition at the exit point from the factory. Storage costs is made up of the cost of holding the materials, parts and retired products before manufacturing as well as the cost of holding the finished product before shipping out to customers. Handling costs consist of the cost of transferring the materials, parts and products from the point of arrival at the factory through various stages of processing to the point of leaving the factory. In this work, all costs associated with

retired product acquisition that varies directly with the quantity taken back are treated as variable material cost. All other costs whether semi-variable or fixed are treated as fixed material cost.

New parts, subassemblies and assemblies used in industrial processes are obtained in various ways, namely: by in-house manufacture, by purchasing, by sub-contracting the production of the parts to other firms, or from other divisions of the same firm. New parts are only treated as direct materials when sizeable quantity of these materials is used as replacement parts, otherwise they are regarded as indirect materials. Indirect material cost is treated as a cost category under factory overhead. Cost of in-house manufactured parts' materials is the cost of parts manufactured by the same firm/plant. Subject to the manufacturing process being used, the slug being used per unit part is made up of quantity of the material that actually become the product and the various material losses that are peculiar to the part manufacturing process used. Purchased parts' cost are product parts purchased outside the firm. This is relevant to PLET options under part replacement operation that is embarked upon if the part cannot be reconditioned. The purchased parts cost refers to the cost of standard parts such as belts, electric motors, pulleys, electronic control panels and others. Cost of interdivisionally transferred parts is considered relevant in cases where firms are made up of plants, divisions or designated as profit- and cost centres such that the cost accounting system is decentralised. In such cases, the Plant receiving parts from another Plant is debited for what is transferred to them, either at cost of production, factored cost, or on profit. However this may otherwise be treated as purchased parts. In such situation this sub-module may be discarded. From the on going, the direct materials costs can generally be expressed as:

$$C_{DM} = q_{rtd}\, c_{rtd} + C_{opc}$$
$$c_{rtd} = c_{acq} + c_{st} \qquad (2.5)$$

where q_{rtd} Quantity of retired product for the period under consideration

c_{rtd} Unit cost of retired product

c_{acq} Acquisition cost per unit retired product

c_{st} Sales tax per unit retired product

C_{opc} Total costs of any outside processing such as transportation charges, including freight, insurance, storage, customs, duty charges and labour charge as well as other expenses on the material

2.1.1.2 Manpower costs

Manpower costs is here used to include all costs associated with the utilisation of human resources in extending the life of a product. It is made up of direct labour cost, indirect labour cost and other labour related costs. In this decision context, direct labour cost is variable while indirect labour cost as well as other labour associated costs are either semi-variable or fixed. Therefore, the direct labour cost is treated as variable cost and the last two are treated as fixed cost under factory overhead. Direct labour C_{DL} consists of all labour that can be specifically identified with a product or service in an economically feasible manner, that is, the labour expended directly on the direct material. The direct labour cost can therefore be evaluated from the expression:

$$C_{DL} = \sum_{w=1}^{N_w} t_w w_w N_{tw} \tag{2.6}$$

where w_w Wage rate of the worker type involved in the PLET

t_w Time duration in which the worker type worked on the PLET

N_{tw} Number or quantity of the particular worker type involved

w Types or categories of workers 1,2,..., N_w involved

2.1.1.3 Factory overhead

This refers to all costs necessary for the product life extension process except direct labour and direct materials. It consists of the costs of indirect material, indirect labour, and all other factory costs that cannot easily be traced to a specific product, including plant depreciation, machinery and equipment depreciation, rent, insurance, taxes, maintenance, power, heat, light, supplies, and small tools. Thus, the factory overhead is:

$$C_{FO} = C_{IDM} + C_{IDL} + C_{OPE} \tag{2.7}$$

where C_{FO} Factory overhead

C_{IDM} Indirect material cost

C_{IDL} Indirect labour cost

C_{OPE} Operating expenses

- **Indirect material costs**

Indirect materials consist of all materials not categorised as direct materials. They are small materials that become part of the product or are consumed otherwise in the production of the product [ANCL 91]. These consist of items such as liaisons, supportive materials and supplies. Liaisons and joining materials, also referred to as connectors, are materials that are not significant on 'per unit' basis. Such materials include glue, rivets, nails, screws, powders and others. The term product supportive material is here used to refer to materials that go into newly reworked product at manufacture for its efficient operation during utilisation. Among such materials are lubricant, grease, coolants, and so on. Process supportive materials are materials that are used in PLET to facilitate the manufacture of the product. Such include lubricants, grease, coolants, and other materials used by process machinery for efficient operation. In this work, supplies refer to the costs of papers, printed materials, and others. The indirect costs can then be obtained from the expression:

$$C_{IDM} = \sum_{typ=1}^{N_{typ}} \left[\sum_{tim=1}^{N_{tim}} c_{tim} \right]_{typ} \qquad (2.8)$$

where c_{tim} Amount expended on individual cost element on the quantity of indirect material in the period under consideration

tim Individual cost element of a type of indirect material 1, 2,…, N_{tim}

typ Type 1, 2, …, N_{typ} of specific items like cost elements, specifications, etc

- **Indirect labour costs**

Indirect labour is the labour that cannot easily be traced to a product or service but is usually associated with a department or several segments of the firm. In this work, indirect labourers are workers that record, supervise, manage, purchase, advise, or support the direct workers. Indirect labour that falls under variable manufacturing overhead include the wages of janitors, inspectors and low level supervisors such as foremen. This cost category can be obtained from the expression:

$$C_{IDL} = \sum_{ct=1}^{N_{ct}} (N_w w_s)_{ct} \qquad (2.9)$$

where $(w_s)_{ct}$ Average wages and salary of the workers in the category per period

$(N_w)_{ct}$ Number of a category of worker associated with the quantity of product

ct Labour categories 1, 2,…, N_{ct}

- **Operating expenses**

Operating expenses as used here refer to costs incurred as a result of engaging in the business of extending product lifecycle. These consist of all costs that are not accounted for under direct and indirect material and labour costs. These costs may or may not be directly dependent on the volume of production. The sub-modules under this category include operation charges, machinery utilisation costs, energy costs, depreciation of factory buildings and machinery, and insurance of factory facilities. Operation charges include all government- and trade group charges such as exercise duties, property taxes, dues charged by government for engaging in the trade line and trade group membership dues. Machinery utilisation cost is the cost of using machines and equipment to manufacture the PLET option finished product. Factory utilities cost is the cost of energy used in machinery priming, in heating, in cooling and in lighting as well as the cost of water and air consumed in the course of manufacturing. Other labour related costs consist of incentive pay for performance above minimum levels such as bonuses, overtime premium, or shift differentials pay, the employer's payroll taxes paid, and fringe benefits such as insurance or vacations. Others are overtime, idle time, payroll fringe costs, and so forth. Idle time cost represent wages paid for unproductive time caused by any work stoppage such as machine breakdowns, material shortages and others. Payroll fringe costs implied here include various employment-related costs such as contributions to social security, hospitalisation plan, pension plans and life insurance. These expenses can be evaluated from the expression:

$$C_{OPE} = C_{OLR} + C_{MUC} + C_{UMFT} \tag{2.10}$$

$$C_{OLR} = \sum_{typ=1}^{N_{typ}} (c_{lr})_{typ}$$

$$C_{MUC} = \sum_{m=1}^{N_m} \left(\sum_{op=1}^{N_{op}} t_{op} m_{op} N_{op} \right)_m$$

$$c_{UMFT} = \left(\sum_{u=1}^{N_u} q_u p_u \right)_{mft}$$

where C_{OPE} Operating expenses

C_{OLR} Other labour related costs

C_{MUC}	Machinery utilisation cost
C_{UMFT}	Utility consumption cost
$(c_{lr})_{typ}$	Other labour related cost type per period
$(m_{op})_m$	Machine type m involved in operation op
op	The particular operation 1,2, …, N_{op} of the process
$(t_{op})_m$	Time duration in which the machine type m is involved in operation op
$(N_{op})_m$	Number of the particular machine type m involved in operation op
m	Machine types 1, 2, …, N_m used in the process
q_{rwd}	Quantity of product reworked per period (month)
u	Utility type 1, 2, …, N_u used in the period
q_u	Quantity of the utility type, u, used per period
q_p	Quantity of product for which the utility type, u, is used
p_u	Utility type rate, DM/month
c_{efo}	Factory operating cost element value
mft	With regard to factory

2.1.1.4 Administrative and selling costs

These costs are made up of all administrative expenses and costs of selling the reworked product. Sales cost includes all costs incurred in an attempt to facilitate the sales of the reprocessed goods. Among the cost elements under this module are sales salaries expense, advertising expense, delivery wages expense, delivery equipment insurance expense, shipping supplies expense, delivery equipment depreciation expense. Under marketer category of decision-makers and cascading option, some of the sales costs may be regarded as direct costs while the rest are regarded as sales overhead. Advertisement cost is the cost of promoting the sales of PLET finished product in various information media such as television, radio, printed media, internet and others. Infrastructural related sales cost include the cost of extending utilities to the sales centre and the cost of giving face-lift to the sales facilities. Sales utilities cost is the cost of energy, heat, water and other utilities consumed in the sales sector. Administrative cost includes all the expenses necessary for the maintenance of an efficient management administration. These include insurance premium for administrative building, personnel, and periodic taxes and dues that do not vary with the quantity of products manufactured. It also includes office salaries expenses, miscellaneous general expense, bad debts expense, office equipment depreciation expense, and office

supplies expense. In this work, administrative and selling costs are overheads which when added to the factory cost give the cost of good sold. These costs can be expressed as:

$$C_{ASO} = C_{SO} + C_{AO} \tag{2.11}$$

$$C_{SO} = \sum_{slt=1}^{N_{slt}} c_{slt}$$

$$= C_{ADV} + C_{IRSC} + C_{SUC}$$

$$C_{SUC} = \left(\sum_{u=1}^{N_u} q_u \, p_u \right)_{sl}$$

$$C_{AO} = \sum_{typ=1}^{N_{typ}} (c_{adm})_{typ}$$

where

C_{ASO}	Administrative and sales expenses
C_{SO}	Sales overhead
C_{AO}	Administrative expenses
C_{ADV}	Advertising cost
C_{IRSC}	Infrastructure related sales cost
C_{SUC}	Sales utilities cost
sl	With regard to sales
c_{slt}	Value of sales cost element type *slt*
slt	Sales cost element type 1, 2,…, N_{slt}
$(c_{adm})_{typ}$	Value of administrative cost element type *typ*

2.2.2 Market attribute

In assessing the various PLET options, the availability of needed spare parts and materials in quantity and quality conformable for the PLET option requirements has to be determined. The marketability of the finished product from a PLET also has to be assessed. This can be achieved by evaluating the work materials and parts supply as well as the demand for the finished product of the process. Figure 2.6 (page 31) shows the elements of market attributes used in evaluating the availability of parts for reprocessing the product and for marketing the reprocessed product. Therefore, the market score is:

$$M_{PLET} = M_{SUP} + M_{DMD} \tag{2.12}$$

where M_{SUP} Supply score of resources required by the PLET to reprocess the product

M_{DMD} Demand score of the PLET reprocessed product

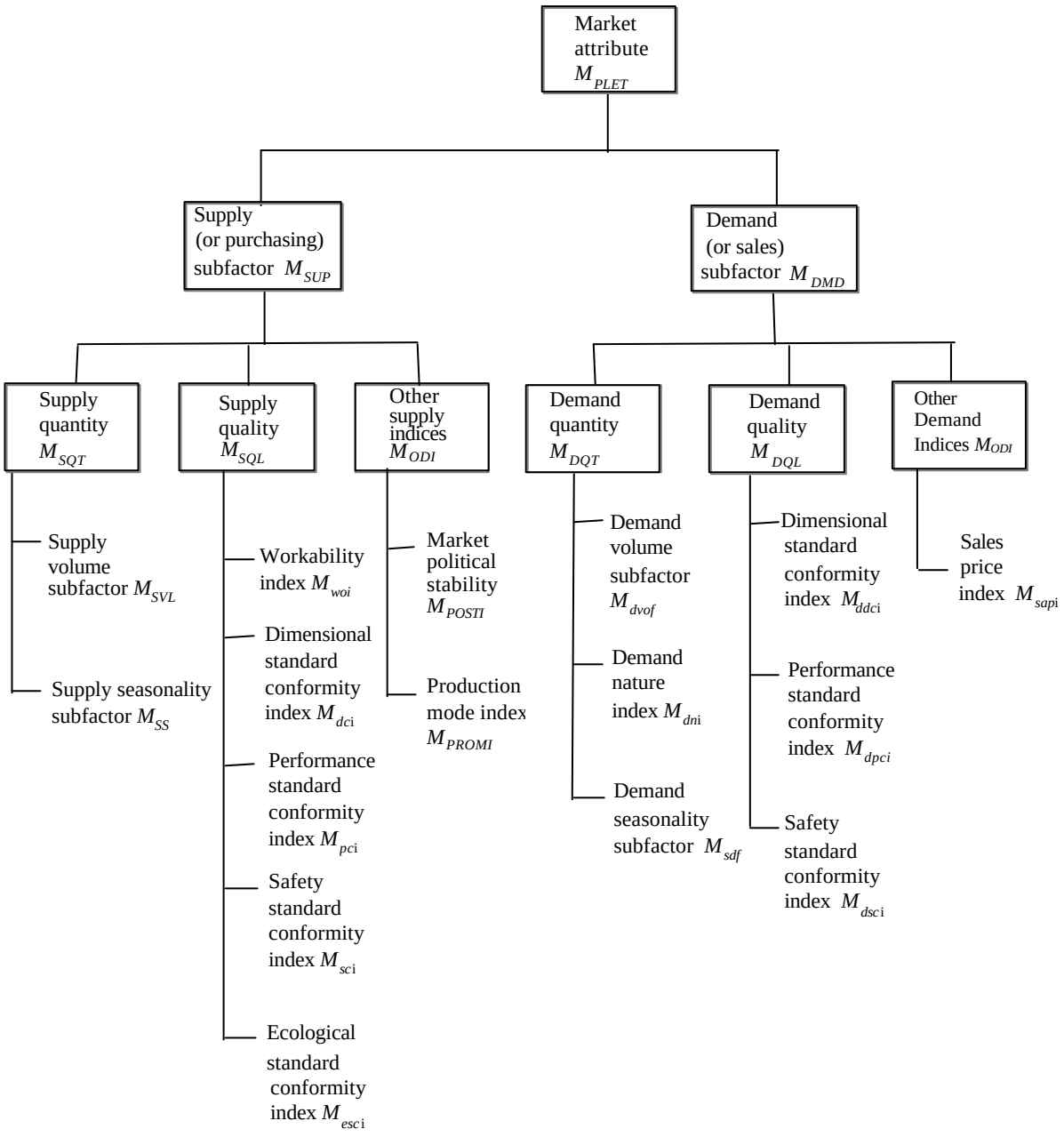


Figure 2.6: Elements of market attribute

2.1.2.1 Supply sub-attribute (M_{SUP})

The suitability of materials and parts for rework has to be assessed in terms of their availability, quality, and fairness of their price. These consequently affect the marketability of the product in terms of the capacity utilisation, final cost of production, the product quality and consequently the profit. This sub-factor evaluates the quantity of parts and

materials available for use in extending the life of a product. The adequacy of the available working materials and parts in product life extension varies with the PLET. Volumetric availability of parts as well as regularity of parts supply is needed for planning the scale of operation by the firm involved. The correlation of these supply parameters can be expressed as:

$$M_{SUP} = M_{SQT} + M_{SQL} + M_{ODI} \quad (2.13)$$
$$M_{ODI} = M_{PROMI} + M_{POSTI}$$

where M_{SQT} Supply quantity score
M_{SQL} Supply quality score
M_{ODI} Other supply indices
M_{PROMI} Production mode index
M_{POSTI} Purchasing market stability index

- **Supply quantity factor (M_{SQT})**

Remanufacturing is a mass production process suited for handling large production volume. The assessment of parts and materials supply is necessary to determine if the available volume of materials and parts supply can meet the required production capacity. Under flexible material and part volume requirement, the evaluation of volumetric availability of material is arrived at by finding the ratio of currently available volume of material to the peak volumetric supply of the material type in 20 years if actual data is available. The 20 years peak period is arbitrarily chosen as the basis of supply volume M_{SVL} determination on the consideration that it is a time long enough to evaluate the stability of materials and parts supply. The peak period can be varied according to site specific determination. In the case of non-availability of actual data, one can make a subjective estimation of the supply index. The basis of subjective volumetric rating should be by personal judgement and comparison of the present volumetric availability of the materials to the known peak volumetric availability of the material in question. The quantitative availability of materials and parts is both time (t) and site-specific (s_i). Seasonality of supply factor M_{SS} evaluates the availability of materials and parts over time.

The relevancy of the sub-sub market attribute arises from the availability of some materials and parts at some period of time of the year. Sometimes, the availability of some of the parts and materials in a required quality is only possible at certain period of the year,

although they are available in the right volume all year round. The seasonality may be evaluated in terms of the days in a week, weeks in a month, weeks in a year, months of the year, years in a decade, or years in a century. In that case, the denominator will be replaced as appropriate. The current denominator shows that the evaluation is in terms of months of availability per year. When actual data are not available, subjective estimation can be made as ratio of estimated period, in months, of availability of the parts and materials per year. The supply quantity can be evaluated from the expression:

$$
\begin{aligned}
M_{SQT} &= (s_i, t) \\
&= M_{SVL} + M_{SS} \qquad (2.14)
\end{aligned}
$$

$$
M_{SVL} = \begin{cases}
\dfrac{1}{N_{pr}} \displaystyle\sum_{pr=1}^{N_{pr}} (q_{su})_{pr} & \text{for all } (q_{su})_{pr} \neq 0 \text{, under } ifl \\
0 & \text{for any } (q_{su})_{pr} = 0, \text{ under } ifl \\
\dfrac{1}{N_{pr}} \displaystyle\sum_{pr=1}^{N_{pr}} \left(\dfrac{\displaystyle\sum_{suso=1}^{N_{suso}} q_{suso}^{cu}}{\displaystyle\sum_{suso=1}^{N_{suso}} q_{suso}^{20y}} \right)_{pr} & \text{if } (q_{su})_{pr} \text{ is under } fl
\end{cases}
$$

$$
= \frac{1}{N_{pr}} \sum_{pr=1}^{N_{pr}} q_{pr}^{fr} \text{ (subjective)}
$$

$$
(q_{pr})_{su} = \begin{cases}
1 & \text{if } (q_{pr})_{av} = (q_{pr})_{rqd} \\
0 & \text{otherwise}
\end{cases}
$$

$$
M_{SS} = \frac{1}{12 N_{pr}} \sum_{pr=1}^{N_{pr}} \left(\sum_{mth=1}^{N_{mth}} N_{mth} \right)_{pr} \text{ (deterministic)}
$$

$$
= \frac{1}{N_{pr}} \sum_{pr=1}^{N_{pr}} srs_{pr}^{fr} \qquad \text{(subjective)} \qquad (2.15)
$$

where

s_i	Site
t	Time
M_{SVL}	Supply volume
M_{SS}	Seasonality of supply score

q_{suso}^{cu} Current quantity of material type *r* supplied by supply source, *suso*

q_{suso}^{20y} The largest quantity of part/material type *pr* supplied in 20years by supply source *suso*

pr Part/material types 1,2, …, N_{pr} or with regard to Parts/materials

q_{pr}^{fr} Subjective supply volume rating of part/material type *pr* chosen from Table 2.2

$(N_{mth})_{pr}$ Number of months in a year in which the part/material type *pr* is supplied

srs_{pr}^{fr} Rating of the fuzzy estimated supply seasonality of part/material type *pr* (Table 2.3)

suso Supply source 1,2,…, N_{suso}

ifl Inflexible requirement

fl Flexible requirement

q_{su} Quantity of supply

Supply quantity available	Volumetric rating
Very large	0.9
Large	0.7
Medium/average	0.5
Low	0.3
Very low	0.1

Table 2.2: Volumetric availability of parts and materials

Regularity of supply	Regularity of supply rating
Always	0.9
Often	0.7
Usually	0.5
Occasionally	0.3
Rarely	0.1

Table 2.3: Regularity of supply rating

- **Supply quality factor (M_{SQL})**

Workability, dimensional conformity, performance conformity, safety and ecological standard conformity are the parameters used in this work to assess the supply quality[1]. These quality parameters' evaluation is to be carried out only for those parts/materials which affect the quality of finished product or for which there is legal and/or technical

[1] Quality is the totality of features and characteristics of a product or service that bear on its ability to satisfy customer needs [KOAR 97].

requirement to use part/material that conform to such specifications. The selective usage of the quality conformity indices for parts/materials is essential to reduce computation time and effort. The supply quality score can be evaluated from the expression:

$$M_{SQL} = M_{dci} + M_{pci} + M_{sci} + M_{esci} + M_{woi} \quad (2.16)$$

Where M_{SQL} Supply quality score for the PLET option

M_{dci} Dimensional conformity index with regard to parts/material supply

M_{pci} Performance conformity index with regard to parts/material supply

M_{sci} Safety conformity index with regard to parts/material supply

M_{esci} Ecological specification conformity index of the parts and materials needed by the PLET option

M_{wor} Workability index with regard to parts/material supply

Dimensional conformity index

Dimensional conformity index evaluates how relevant dimensions of the parts and materials conforms to standards that meets the dimensions needed for rework such that it will fit into the designed product geometry and perform functionally satisfactorily well in the product. All relevant dimensional types are evaluated for a material or part. Dimensional conformity index for a part is scored zero under inflexible dimensional requirements when a part fails to meet the required standard for a dimensional type. Otherwise, it is scored one. Under flexible dimensional requirement, dimensional conformity index is the ratio of the dimension of the part/material to the dimensional standard. The relevance of dimensional conformity index under supply sub-attribute stem from the fact that a number of used parts may no longer be useful after being reworked, because they will not fit into the product geometry or will not function satisfactorily in the product geometry after being worked. Thus, the dimensional conformity score of a PLET with regard to the parts/materials for product rework can be obtained from table 2.5 or from the expression:

$$M_{dci} = \frac{1}{N_{pr}} \sum_{pr=1}^{N_{pr}} (dcs)_{pr}$$

$$dcs_{pr} = \begin{cases} 0 & \text{for at least one } \left(dcr_{pr}\right)_{typ} = 0 \\ \dfrac{1}{N_{typ}} \sum_{typ=1}^{N_{typ}} \left(dcr_{pr}\right)_{typ} & \text{for no } \left(dcr_{pr}\right)_{typ} = 0 \end{cases}$$

$$(dcr_{pr})_{typ} = \begin{cases} 1 & \text{if } d_{sp} = (d_{rqd}) \text{ and } (d_{rqd}) \text{ is under } ifl \\ 0 & \text{if } d_{sp} \neq (d_{rqd}) \text{ and } (d_{rqd}) \text{ is under } ifl \\ \left(\dfrac{d_{av}}{d_{rqd}} \right)_{pr} & \text{for } d_{rqd} \text{ under } fl \end{cases} \qquad (2.17)$$

where dcs_{pr} Dimensional conformity score of the part or material pr

$(dcr_{pr})_{typ}$ Dimensional conformity rating of the material or part pr with respect to the dimensional type

$(d_{sp})_{pr}$ Dimensional standard specification, a specific type, of the part or material pr available on the market

$(d_{rqd})_{pr}$ Type of dimensional specification of the part or material pr needed for the product quality

$(N_{ald})_{pr}$ Number of variations in the particular specification type allowed by the market with respect to the part or material pr

$(N_{av})_{pr}$ Number of variations in the particular specification type available with respect to the part or material pr

Performance conformity index

Performance standard conformity assesses how well the functionality of the part or material conforms to the standard required in the PLET option finished product quality. The part is assessed for each performance type by comparing the performance specification of the part/material with the required standard. The sum of the ratings of all performance types is found for relevant parts and materials. This is followed by the compilation of performance scores for the parts and materials with regard to the PLET option in order to obtain the performance specification index for the PLET. This can be evaluated subjectively from table 2.5 or by calculation from the expressions:

$$M_{pci} = \frac{1}{N_{pr}} \sum_{pr=1}^{N_{pr}} \{pcs\}_{pr}$$

$$pcs_{pr} = \begin{cases} 0 & if\ any\ (pcr_{pr})_{typ} = 0 \\ \dfrac{1}{n_{typ}} \sum_{typ=1}^{N_{typ}} (pcr_{pr})_{typ} & if\ no\ (pcr_{pr})_{typ} = 0 \end{cases}$$

$$(pcr_{pr})_{typ} = \begin{cases} 1 & \text{if } p_{sp} = p_{rqd} \text{ and } p_{rqd} \text{ is under } ifl \\ 0 & \text{if } p_{sp} \neq p_{rqd} \text{ and } p_{rqd} \text{ is under } ifl \\ \left(\dfrac{p_{av}}{p_{rqd}} \right)_{pr} & \text{for } p_{rqd} \text{ under } fl \end{cases}$$

(2.18)

where pcs_{pr} Performance conformity score of the part or material

$(pcr_{pr})_{typ}$ Performance specification type rating for the part

p_{sp} The standard of a specific performance specification of the part or material pr (nearest to p_{rqd}) that is available on the market

p_{rqd} A specific performance specification of the part or material pr needed for the product quality.

Safety conformity index

Safety standards conformity index refers to how safe a part or material is in using it to rework a product. This safety factor has to do both with the safety of the worker and the safety of the part or material during the rework process. The safety of the material or part during manufacturing is a function of fragility of the part or material. The evaluation of the part or material for safety is made in two facets, namely, the conformity of the materials to minimum safety standard and the conformity to the optimal or ideal safety standard. The degree of safety of a part/material contributes to the final safety of the finished product. Effort to improve the safety standard of the finished product will consequently increase the cost of production. Safety conformity score is therefore obtainable subjectively from table 2.5 or from the expressions:

$$M_{sci} = \frac{1}{N_{pr}} \sum_{pr=1}^{N_{pr}} (scs)_{pr}$$

$$(scs)_{pr} = \begin{cases} 0 & \text{for at least one } (mscr_{pr})_{typ} = 0 \text{ (for minimum safety requirement) or at least one } (iscr_{pr})_{typ} = 0 \text{ (for optimal safety requirement) and both are under } ifl \\ \dfrac{1}{N_{typ}^{mscr}} \sum_{typ=1}^{N_{typ}} (mscr_{pr})_{typ} & \text{for all } (mscr_{pr})_{typ} \neq 0, \text{ for minimum safety requirement under } fl \\ \dfrac{1}{N_{typ}^{iscr}} \sum_{typ=1}^{N_{typ}} (iscr_{pr})_{typ} & \text{for all } (iscr_{pr})_{typ} \neq 0, \text{ for optimal safety requirement under } fl \end{cases}$$

$$(mscr_{pr})_{typ} = \begin{cases} 1 & \text{if } pr \text{ must meet minimum safety specification types requirement and } (s_{sp})_{pr} = (s_{rqd})_{pr} \\ 0 & \text{if } pr \text{ must meet minimum safety specification types requirement and } (s_{sp})_{pr} \neq (s_{rqd})_{pr} \\ \left(\dfrac{s_{sp}}{s_{rqd}}\right)_{pr} & \text{for permissive safety conformity} \end{cases}$$

$$(iscr_{pr})_{typ} = \begin{cases} 1 & \text{if } pr \text{ must meet ideal safety specification type's requirement and } \left(s_{sp}\right)_{pr} = \left(s_{iss}\right)_{pr} \\ 0 & \text{if } pr \text{ must meet minimum safety specification type's requirement and } \left(s_{sp}\right)_{pr} \neq \left(s_{iss}\right)_{pr} \\ \left(\dfrac{s_{sp}}{s_{iss}}\right)_{pr} & \text{for permissive safety conformity} \end{cases}$$

(2.19)

where scs_{pr} Safety conformity score of the part or material

$(iscr_{pr})_{typ}$ Ideal safety conformity score of the specific specification type of a part or material

$(mscr_{pr})_{typ}$ Minimum safety score of the specific specification type for the part or material

$(s_{sp})_{pr}$ Value of specific safety specification type for the part or material *pr* that is available on the market

$(s_{rqd})_{pr}$ Minimum value of the specification type for the part or material *pr* needed for the product quality.

$(s_{iss})_{pr}$ Optimal safety specification value of the part or material *pr*

Ecological standard conformity index

Ecological standard conformity index assesses the conformity of the part to the ecological policy or standard of the firm. This standard is evaluated in terms of toxic material content of the part or material, resource consumption by the part, and waste generation arising from the usage of the part. This index can be obtained from the expression:

$$M_{esci} = \frac{1}{N_{pr}} \sum_{pr=1}^{N_{pr}} escs_{pr}$$

$$\left(escs_{pr}\right)_{typ} = \begin{cases} 0 & \text{if any } \left(escr_{pr}\right)_{typ} = 0 \text{ and under } ifl \\ \dfrac{1}{N_{typ}} \sum_{typ=1}^{N_{typ}} \left(escr_{pr}\right)_{typ} & \text{otherwise} \end{cases}$$

$$(escr_{pr})_{typ} = \begin{cases} 1 & \text{if } (ev_{pr})_{typ} \text{ is better or equal to } (es_{pr})_{typ} \text{ under } ifl \\ 0 & \text{if } (ev_{pr})_{typ} \text{ is worse than } (es_{pr})_{typ} \text{ under } ifl \\ \left\{\left(\dfrac{ev}{es}\right)_{pr}\right\}_{typ} & \text{for flexible standard} \end{cases}$$

(2.20)

where $escs_{pr}$ Ecological conformity score of the part/material *pr*

$(escr_{pr})_{typ}$ Part or material's conformity rating on ecological type's standard

$(ev_{pr})_{typ}$ Environmental value of the part/material *pr* with regard to the specific environmental index such as toxicity, durability, etc.

$(ev_{pr})_{typ}$ Environmental standard value required of the part/material *pr* with regard to the specific environmental index

Workability standard conformity index

Workability index evaluates ease of use of the parts/material in the particular process. This sub-module evaluates the extent of treatment required by the material before meeting the functional requirement in the product. The workability index being process specific, can be

evaluated in terms of weldability, machinability, castability, formability, and so on. The workability of a material that will be subjected to more than one process is the average of the sum of its individual workability values. The workability score can be obtained from the equations:

$$M_{woi} = \begin{cases} 0 & \text{if at least one } wos_{pr} = 0 \\ \dfrac{1}{N_{pr}} \sum_{pr=1}^{N_{pr}} (wos)_{pr} & \text{if no } wos_{pr} = 0 \end{cases} \tag{2.21}$$

$$wos_{pr} = \begin{cases} 1 & \text{if the workability index type is both significant and inflexible as well as meets the required minimum workability rating with respect to a PLET} \\ 0 & \text{if it fails to meet the required minimum workability rating} \\ \in [0,1] & \text{if the workability index type is flexible} \end{cases}$$

where wor Workability rating of the material or part

wos_{pr} Score of the workability of the part or material type

N_{pr} Number of part or raw material types involved

Ease of working	**Ease of working/reworking rating,** *wos*
Very easy	1
Easy	0.75
Relatively uneasy	0.5
Difficult	0.25
Very difficult	0.1
Unworkable or unreworkable	0

Table 2.4: Workability/reworkability assessment of parts and materials

Degree of conformity	**Conformity index**
Meets required standard	1
Manageable after some modification	0.5
Unfit for the purpose	0

Table 2.5: Evaluation table for assessing the degree of part and materials' conformity to required standard

Market policy	Market policy rating *mps*	Environmental control on parts and materials	Environmental policy rating *epr*
Free deregulated economy	1	Mandatory, hard to fulfil control	0.3
Partially free but with price and few other control	0.5	Permissive	0.6
Closed market economy	0	Non-existing	0.9

Table 2.6: Eco-market policy characteristics

- **Other supply indices (M_{ODI})**

Production mode index

This refers to the production mode of the parts and materials needed for the PLET option, whether it is custom produced or mass produced in which case the parts and materials are purchased from the market. The relevance stems from the fact that custom-produced parts and materials have more advantages than mass-produced parts, because manufacturers and suppliers can be directed to produce such parts and materials to a special set of specifications. This index value can be obtained from the expression:

$$M_{PROMI} = \frac{1}{N_{pr}} \sum_{pr=1}^{N_{pr}} \left(M_{promos}\right)_{pr} \tag{2.22}$$

where M_{promos} Production mode score of the part or material type (Table 2.7)

Production mode *pm*	Cost minimisation tendency *cmt*	Customer's need satisfaction tendency *cnst*	Production mode M_{promos}
Continuous (large volume production)	0.9	0.3	0.6
Customer requirement oriented production	0.6	0.9	0.75
Batch production	0.3	0.6	0.45

Table 2.7: Production mode assessment

Purchasing Market Political stability

Political stability of a market site/state will affect the availability of the parts and materials. It will also affect the price of materials. The political stability is assessed in terms of the frequency in the change of leadership, the degree of peace and tranquillity within the state

as well as by the goodwill enjoyed by the state in the international community. The relationship can be expressed as:

$$M_{POSTI} = \sum_{pr=1}^{N_{pr}} \left(\frac{M_{fcs} + M_{irs} + M_{ips}}{3} \right)_{pr} \quad (2.23)$$

where M_{ips} Internal peace and security rating (use Table 2.8 on page 42)

M_{fcs} Frequency of change in government rating (use Table 2.9 on page 42)

M_{irs} International relation rating (use Table 2.10 on page 42)

Degree of peace and security within the state	**Internal peace and security rating** M_{ips}
1. Very good relationship between populace 2. Very good relationship between people and government	0.9
When there is occasional disturbance in one of the two	0.7
When there is occasional disturbance in both	0.5
When there are uneasy calm in the state	0.35
When there are frequent disturbance in any of the above	0.2
When there are frequent disturbance in both cases	0.1

Table 2.8: Internal peace and security assessment

Frequency of change of party in power/ type of government in 20 years *fc20*	**Frequency of change rating** M_{fcs}
$fc20 \leq 2$	0.9
$fc20 \leq 4$	0.6
$fc20 \leq 6$	0.35
$fc20 > 6$	0.1

Table 2.9: Power change factor

Degree of peace and security of the state in relationship with the international community	**International relation rating** M_{irs}
Very good	0.9
Good	0.7
Average	0.5
Poor	0.3
Very poor	0.1

Table 2.10: International relation factor

2.2.2.2 Demand sub-attribute (M_{DMD})

Demand sub-attribute assesses the size of market available for the reworked product of the particular quality impacted by the PLET option. The evaluation of demand will enable the firm to forecast the viability of the product on the market, estimate the payback period and plan for expected changes in view of trends in market demand for the PLET option reworked product.

- **Demand quantity factor (M_{DQT})**

The estimation of the expected size of demand is considered to be important in product life extension to the decision makers as they consider economy of production in their choice of product life extension techniques. It is evaluated in terms of demand volume and nature of demand. Demand volume factor assesses the volume of demand for the PLET finished product. Demand nature index is used to evaluate the purpose of demand with the consequent assessment of how this affects the volume of demand and stability of demand. Seasonality of demand is aimed at assessing the duration of demand for the PLET finished product per year. The relevance of this sub-sub attribute derives from comparing the duration of demand for a PLET finished product quality with the other PLET option finished product, thereby getting insight to the option that has the best evenly distributed demand per year. The subjective seasonality of demand rating is made by experienced decision-maker that can adjudge the variation in demand over the times of the year. The demand quantity score can thus be obtained from:

$$M_{DQT} = M_{dvof} + M_{dni} + M_{sdf} \tag{2.24}$$

$$M_{dvof} = \begin{cases} \dfrac{\sum_{cptr=1}^{N_{cptr}} q_{cptr}}{q_{dcm}} & \text{if data exist} \\ \in [0,1] & \text{else choose from Table 2.10} \end{cases}$$

$$M_{dni} \in [0, 1] \quad \text{(choose from Table 2.11) (subjective)}$$

$$M_{sdf} = \begin{cases} \dfrac{N_m^d}{12} & \text{if data exist} \\ \in [0,1] & \text{else choose from Table 2.12} \end{cases}$$

where M_{DQT} Demand quantity score

M_{dvof} Demand volume score

M_{dni} Demand nature index

M_{sdf} Seasonality of demand

q_{cptr} Quantity of the product supplied by competitor *cptr*

q_{dem} Estimated quantity of the product demanded

M_{dqs} Quantity of demand rating

N_m^d Number of months in a year in which the product is demanded

cptr Competitor 1, 2, …, N_{cptr}

Demand quantity	**Demand quantity rating**, M_{dqs}
Very large	0.9
Large	0.7
Medium	0.5
Low	0.3
Very low	0.1

Table 2.11: Subjective demand volume rating

Demand situation	**Situation rating**	**Demand nature**	**Demand nature rating** M_{dni}
1. Part inclusion is mandatory	0.35	Situations 1 & 2 holds	1
		Only situation 1 holds	0.65
2. No substitute	0.35	When none of the situations 1 & 2 holds	0.3

Table 2.12: Demand nature characteristics rating

Regularity/seasonality of demand	**Regularity of demand rating** M_{sdf}
Always	0.9
Often	0.7
Usually	0.5
Occassionally	0.3
Rarely	0.1

Table 2.13: Demand regularity/seasonality rating

- **Demand quality factor (M_{DQL})**

This module evaluates reprocessed product demand quality in terms of dimensional-, performance-, and safety conformity of reworked product with the market requirements. Dimensional conformity assesses the conformity of the PLET finished product with the market or industry standard. The relevance stems from the need of the product to meet some standard quality with respect to some important dimensional types. This is scored in relation to the flexibility of the market with regard to the dimensional type. The flexibility of the market is evaluated in terms of mandatoriness of the product's conformity to a particular dimensional type. Performance conformity index is concerned with measuring the PLET finished product in terms of meeting the type's requirement. In the case of machine tools, such performance types include tolerance capability, surface finish capability, production rate and so on. In the case of processing machinery (for example, Sheller), performance types include percentage breakage, throughput capacity, shelling efficiency, and separation efficiency. Safety index of the finished product aims at safety quality of the PLET finished product in comparison with the safety requirement standard of the market. A number of safety measures may be required from the specific product group or by a specific market. Dimensional- and performance specification conformity factors as well as safety score constitute demand quality index. Demand volume factor and demand quality index also constitute customer satisfaction index, *csi*. The demand quality score is obtainable from the expression:

$$M_{DQL} = M_{ddci} + M_{dpci} + M_{dsci}$$

$$M_{ddci} = \begin{cases} 0 & \text{if any of the } M_{dcs} = 0 \\ 1 & \text{if } M_{fbmps} \text{ is not applicable} \\ \left(\dfrac{M_{dcs} + M_{fbmds}}{2} \right)_{rwd} & \text{if none of the two above is valid} \end{cases}$$

$$\left(M_{dcs}\right)_{rwd} = \begin{cases} 0 & \text{if any } (M_{dcrp})_{typ} = 0 \\ \dfrac{1}{N_{typ}} \sum_{typ=1}^{N_{typ}} \left(M_{dcrp}\right)_{typ} & \text{if no } (M_{dcrp})_{typ} = 0 \end{cases}$$

$$(M_{dcrp})_{typ} = \begin{cases} 1 & \text{if } d_{sp} \text{ satisfied } d_{alld} \text{ and the } d_{alld} \text{ is under } ifl \\ 0 & \text{if } d_{sp} \text{ did not satisfy and the } d_{alld} \text{ is under } ifl \\ \left(\frac{d_{sp}}{d_{alld}}\right)_{rwd} & \text{if } d_{alld} \text{ is under } fl \end{cases}$$

$$\left(M_{fbmds}\right)_{\text{rwd}} = \frac{1}{N_{typ}} \sum_{typ=1}^{N_{typ}} \left\{ \left(\frac{N_{alld}}{N_{av}} \right)_{rwd} \right\}_{typ}$$

$$\left(M_{pcs}\right)_{rwd} = \begin{cases} 0 & \text{if any } (M_{pcrp})_{typ} = 0 \\ \frac{1}{N_{typ}} \sum_{typ=1}^{N_{typ}} (M_{pcrp})_{typ} & \text{if no } (M_{pcrp})_{typ} = 0 \end{cases}$$

$$M_{dpci} = \begin{cases} 0 & \text{if any of the } M_{pcs} = 0 \\ 1 & \text{if } M_{fbmps} \text{ is not applicable} \\ \left(\frac{M_{pcs} + M_{fbmps}}{2} \right)_{rwd} & \text{if none of the two above is valid} \end{cases}$$

$$(M_{pcrp})_{typ} = \begin{cases} 1 & \text{if } \left(p_{sp}\right)_{\text{rwd}} \text{ satisfied } \left(p_{rqd}\right)_{\text{rwd}} \text{ and } \left(p_{rqd}\right)_{\text{rwd}} \text{ is under } ifl \\ 0 & \text{if } \left(p_{sp}\right)_{\text{rwd}} \text{ did not satisfy } \left(p_{rqd}\right)_{\text{rwd}} \text{ and } \left(p_{rqd}\right)_{\text{rwd}} \text{ is under } ifl \\ \left(\frac{p_{sp}}{p_{rqd}} \right)_{rwd} & \text{if } \left(p_{rqd}\right)_{\text{rwd}} \text{ is under } fl \end{cases}$$

$$\left(M_{fbmps}\right)_{rwd} = \frac{1}{N_{typ}} \sum_{typ=1}^{N_{typ}} \left\{ \left(\frac{N_{alld}}{N_{av}} \right)_{rwd} \right\}_{typ}$$

$$M_{dsci} = \begin{cases} 0 & \text{if any } M_{mscrp} \text{ or } M_{iscrp} = 0 \text{ under } ifl \\ \dfrac{1}{N_{typ}} \sum_{typ=1}^{N_{typ}} \left(M_{mscrp}\right)_{typ} & \text{for all } M_{mscrp} \neq 0 \text{ and under } fl \\ \dfrac{1}{N_{typ}} \sum_{typ=1}^{N_{typ}} \left(M_{iscrp}\right)_{typ} & \text{for all } M_{iscrp} \neq 0 \text{ and under } fl \end{cases}$$

$$\left(M_{mscrp}\right)_{typ} = \begin{cases} 1 & \text{if } \left(s_{sp}\right)_{rwd} \text{ satisfies or is better tha n } \left(s_{rqd}\right)_{\text{rwd}} \text{ and } \left(s_{sp}\right)_{rqd} \text{ is under } ifl \\ 0 & \text{if } \left(s_{sp}\right)_{\text{rwd}} \text{ does not satisfy } \left(s_{rqd}\right)_{\text{rwd}} \text{ under } ifl \\ \left\{\left(\dfrac{s_{sp}}{s_{rqd}}\right)_{rwd}\right\}_{typ} & \text{if safety specificat ion type is flexible} \end{cases}$$

$$(M_{iscrp})_{typ} = \begin{cases} 1 & \text{if } pr \text{ must meet the ideal safety specification type's requirement and } \left(s_{sp}\right)_{rwd} = \left(s_{iss}\right)_{rwd} \\ 0 & \text{if } pr \text{ must meet the ideal safety specification type's requirement and } \left(s_{sp}\right)_{rwd} \neq \left(s_{iss}\right)_{rwd} \\ \left(\dfrac{s_{sp}}{s_{iss}}\right)_{rwd} & \text{if safety specification type is flexible} \end{cases}$$

(2.25)

where M_{ddci} Market demanded dimensional specification conformity index of the reworked product

M_{dpci} Market demanded performance specification conformity index of the reworked product

M_{dsci} Market demanded safety specification conformity index of the reworked product

$(M_{dcs})_{rwd}$ Preliminary dimensional score of the reworked product

$(M_{pcs})_{rwd}$ Preliminary performance score of the reworked product

$(M_{scs})_{rwd}$ Preliminary safety score of the reworked product

$(M_{dcrp})_{typ}$ Conformity rating of the PLET reworked product with regard to a dimensional specification

$(M_{pcrp})_{typ}$ Conformity rating of the PLET reworked product with regard to a dimensional specification

$(M_{fbmds})_{rwd}$ Flexibility of the market with regard to dimensional conformity requirement of the reworked product

$(M_{fbmps})_{rwd}$ Flexibility of the market with regard to performance conformity requirement of the reworked product

$(M_{mscrp})_{typ}$ Minimum safety conformity rating of the PLET reworked product with regard to a safety specification

$(M_{iscrp})_{typ}$ Optimal safety conformity rating of the PLET reworked product with regard to a safety specification

$(d_{sp})_{rwd}$ The value of a specific dimensional specification type for the PLET option reworked product

$(d_{alld})_{rwd}$ Standard value of the dimensional specification type that meets the required reworked product quality.

$(N_{alld})_{rwd}$ Number of variations in the particular specification type allowed by the market with regard to the reworked product

$(N_{av})_{rwd}$ Number of variations in the particular specification type that are available with regard to the reworked product

$(p_{sp})_{rwd}$ Standard value of the performance specification type for the product

$(p_{rqd})_{rwd}$ Required value of the performance specification type for the product

$(s_{sp})_{rwd}$ Value of safety specification type for the PLET reworked product

$(s_{rqd})_{rwd}$ Minimum value of safety specification type required by the market for the reworked product

$(s_{iss})_{rwd}$ Optimal safety standard value of the reworked product

- **Other demand index (M_{ODI})**

The only other demand index identified in this work is sales price index. It assesses the fairness of a PLET option finished product price to the price of substitute or to competitors' price. This is relevant in terms of how well the product can compete with substitute in the market with respect to price. Sales price index is obtainable from the expressions:

$$M_{sapi} = 1 - \frac{p_{isp}}{p_{sub}} \; ; i = 1, 2,... \qquad (2.26)$$

$$p_{isp} = C_{PLET} + p_{dpm}$$

where M_{sapi} Sales price index

C_{PLET} Total cost of the PLET option per product

p_{dpm} Desired profit margin

p_{isp} Intended sales price of the reworked product

p_{sub} Average price of the substitute

2.2.3 Time attribute

Time estimation is important for PLET planning in that it among other things facilitates cost estimation i.e. cost of reprocessing a unit product and consequently the study of the economics of product life extension. Knowing the time it takes to carryout each operation constituting a PLET on a product is also invaluable when analysing product designs for ease of carrying out such operations, thus bringing about improvement in future designs [DOKE 97]. The time attribute is seen and evaluated from two dimensional views, namely, the time required to carry out the reprocessing as a function of the facilities available and the time stipulated by customer. Figure 2.7 shows the considered elements of time attribute.

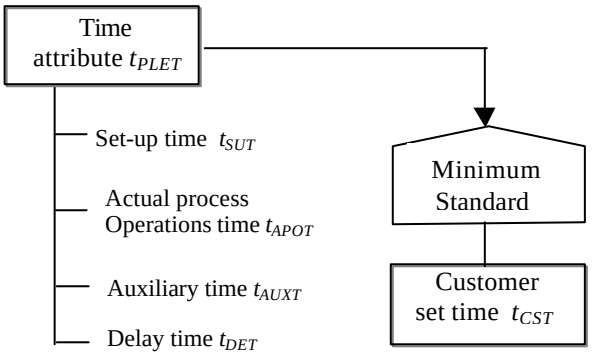


Figure 2.7: Time attribute elements

2.2.3.1 Process time

This refers to the time required to rework a unit product to the required functional standard. Given a set of facilities or process path consisting of a number of operations, the operational time period to complete an assignment can be determined from set-up time, the machine work rate such as machining time, transfer time from one machine to another, personnel rate of working, logistic factors, etc. The cost of reworking a unit product can then be evaluated from the knowledge of reworking time. Time is identified and determined for equipment operation and other time data associated with operation, transportation, and supply as an intrinsic part of tasks of a product life extension process analysis. This is needed to obtain man-hour requirement for the PLET option, PLET time standard, and supply support response. Time factors are determined in detail for those functions or functional sequences in which time is critical to mission success, safety, use of resources and so on.

Determination of task times as one of the activities involved in process planning is aimed at evaluating the PLET option capable of producing a projected maximum output of desired quality. Task times determination has long been based on work measurement techniques such as motion-and-time study using stopwatch or video, or motion-and-time analysis using predetermined time standards systems such as method-time-measurement (*MTM*), and work factor (*WF*). In order to use the predetermined time standards, a good understanding of various classes of motions of "getting" and "putting" an object, the object's attributes and relationship with its destination must have been acquired. Predetermined time standards can be used to estimate operational times when planning an assembly line or machines. However due to the micro-definition of motions involved in performing a task, they are not easy to use. A product life extension process analysis revealed that the reprocessing time of a product by a PLET is a function of available resources, product condition, and reworked product's functional quality requirement. This can be expressed as:

$$t_{PLET} = f(REAV, PRCO, FQRE) = t_{SUT} + t_{AUXT} + t_{APOT} + t_{DET} \quad (2.27)$$

where t_{PLET} Estimated required time to carry out the PLET option

t_{SUT} Set-up time

t_{APOT} Actual process operations time

t_{AUXT} Auxilliary times

t_{DET} Delay time

- **Set-up time (t_{SUT})**

According to Salvendy, set-up is said to include work to prepare the machine, process, or bench for product parts or the cycle. And that starting with a machine, process, or bench in a neutral condition, set-up includes punch in/out, paper work, obtaining tools, positioning unprocessed materials nearby, adjusting and inspecting [SALV 92]. Aderoba summarised it by referring to set-up as the total time of all preliminary operations performed before actual operation takes place. It includes time to obtain tools and raw materials from the store, mounting the work piece and the tool, and returning used tool [ADER 94]. This value is obtainable either by experience or time standard data from scientific work-study. In this case, the second definition of set-up is adopted and time standard value is assumed known. The set-up time is thus obtainable from the expression:

$$t_{SUT} = \sum_{op=1}^{N_{op}} \left(t_{ot} + t_{orm} + t_{mwp} + t_{mt} + t_{rt} \right)_{op} \quad \text{hr} \qquad (2.28)$$

where t_{SUT} Set-up time

t_{ot} Time to obtain tool from store

t_{orm} Time to obtain raw materials from store

t_{mwp} Time to mount work piece

t_{mt} Time to mount tool

t_{rt} Time to return used tool

- **Actual process operations time (t_{APOT})**

This refers to the sum of actual times taken to perform individual operations making up the PLET option. The actual time taken to carry out an operation on a product is a function of the product condition, the necessary activities to be carried out to achieve the required product quality and the characteristics of facilities available for carrying out the operation. This can be calculated from:

$$t_{APOT} = f\left(T_{PDCD}, N_{actvy}, T_{TCAP}\right)$$

$$= \sum_{op=1}^{N_{op}} \left(\sum_{actvy=1}^{N_{actvy}} t_{actvy} \right)_{op} \quad \text{hr} \qquad (2.29)$$

where t_{APOT} Actual process operations time

T_{PDCD} Product condition

$actvy$ Activity 1,2,…, N_{actvy} making up a constituent operation

T_{TCAP} Techno-capability of the facilities

t_{actvy} Actual time required to complete each activity constituting an operation

- **Auxiliary time (t_{AUXT})**

This refers to the total time for auxiliary activities connected with operations such as replacement/repositioning of the workpiece, readjustment of tools, tool resharpening and inspection of the work by measurement. This is estimable by experience, by using time standards and/or from the expression:

$$t_{AUXT} = t_{ptrw} + t_{raj} + t_{rsp} + t_{iwm} + t_{rrw} \quad \text{hr} \qquad (2.30)$$

where t_{AUXT} Auxilliary times

t_{ptrw} Portion of tool insert replacement time per workpiece

t_{raj} Tool readjustment time

t_{rsp} Tool resharpening time

t_{rrw} Replacement/repositioning of the workpiece

t_{iwm} Inspection of the work by measurement

- **Delay time (t_{DET})**

This is the time allowed for unavoidable delays (resulting from interruptions made by the supervisor, dispatcher, inspector, material handler, and others during the working day), rest periods, waiting for materials, going to toilet, fatigue allowance and others. It is the time allowed for the employee to maintain his or her general well being. Allowances of 5% of the workday have generally been proved adequate [SALV 92].

$$t_{DET} = a_t t_{wdy} \quad \text{hr} \tag{2.31}$$

where t_{DET} Delay time

a_t Allowable delay as percentage of workday

t_{wdy} Work day (hrs)

2.2.3.2 Customer set time (t_{CST})

For service and contract reprocessing organisations, customer set time is important for corporate image and consequently for continual existence of profit making business. It is therefore a determinant factor in the selection of PLET. It is a function of customer's need and the capability of the reprocessing facility. Customer need here refers to the reprocessed product's functional requirement requested by the customer. This determines the number and extent of each reprocessing operation to which the retired product is subjected. The customer set time can be calculated from the expression:

$$t_{CST} = (1/n_{rwd})(24/n_{whd})\, t_c \quad \text{hr} \tag{2.32}$$

where t_c The delivery time requested by the customer in days

n_{rwd} Number of products to be reworked

n_{whd} Number of working hours per day

2.2.4 Legislative attribute

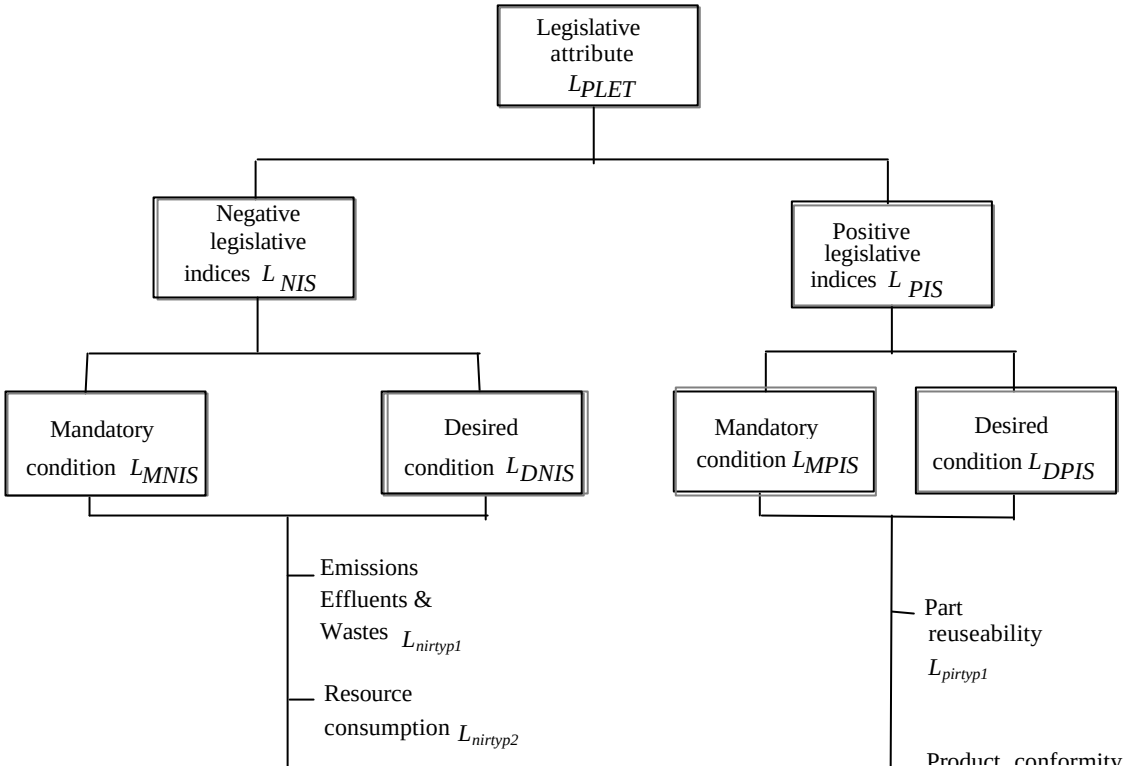
In many European and Asian countries, there is the threat of legislation which will force manufacturers of a number of durable goods to take-back and recycle their products [SPJO 98]. Proactive companies embark on “greening” their product before the arrival of the legislation so that they can be looked upon as the models upon which government will base their rules. Such companies can set some targets and compare the expected/pilot product qualities from their facilities with the targets. Assessment can also be carried out on their products with regard to existing environmental legislation. The results of such evaluations may influence the market in their favour, as this can be used as market strategy. For instance, national, regional and local authorities of some countries and communities like Germany and European Union have set a number of legislative requirements for emissions and environmental quality. The focus of some of these Acts is on product and process quality as regards their emissions, resource consumption and toxic material use. Similarly, a number of policies have been promoted/adopted by various countries of the world to at least reduce, if cannot eradicate, pollution and to reduce the problem of managing non-hazardous solid wastes. Since the past number of years, Germany has instituted a number of programs aimed at solving environmental problems. For example, the Avoidance of Packaging Waste Ordinance also known as Toepfer Decree of 1991, which is an aggressive program designed to collect substantial quantities of recyclable packaging materials and promote the recycling and reuse of materials which attempts eliminating the use of landfills and incinerators, was instituted. There is also a „Regulation on the Avoidance, Reduction and Utilisation of Wastes from Used Electrical and Electronic Equipment“ which directed companies selling electronic products to take back similar equipment from the customer at the time of sale or delivery and to take back products of their own brand at any time. These measures discourage companies from producing a number of environmentally hazardous products and to produce reusable or recyclable products as well as use environmentally friendly process. For instance, before the Toepfer decree of 1991, government has enacted a deposit law on one-way polyethylene terephthalate („PET“) in 1990. Before the protest of European Commission that led to amendment of this law, it adversely affected a number of foreign companies with regard to marketing their products in Germany. Thus entrepreneur has to be well equipped to efficiently identify and assess which national and state/provincial

environmental laws, regulations, and standards will affect their business opportunities. The basis of legislative attribute evaluation of process alternatives in this work is the German waste avoidance, recycling, and disposal act (Kreislaufwirtschafts- and Abfallgesetz_KrW-/AbfG) of 27 September 1994, with particular emphasis on Part 3 Art 22, which is referred to as product responsibility law [KRWG 94]. Thus, the legislative factor is primarily meant to assess the conformity of each PLET option with relevant environmental regulations and/or to evaluate the conformity of each process with the environmental standard set either at the industry level or at the firm level. Environmental standard level set at the firm level could be that which would facilitate achieving competitive advantage. Figure 2.8 on page 54 shows the indices used in assessing the legislative conformity of PLET.

The PLET option score with respect to legislative attribute can be computed from the expression:

$$L_{PLET} = L_{NIS} + L_{PIS} \quad (2.32)$$
$$= L_{MNIS} + L_{MPIS} \quad \text{(mandatory condition)}$$
$$= L_{DNIS} + L_{DPIS} \quad \text{(desired condition)}$$

where L_{MNIS} Negative legislative score of the PLET under mandatory condition
L_{MPIS} Positive legislative score of the PLET under mandatory condition
L_{DNIS} Desired negative indices goals conformity score of the PLET
L_{DPIS} Desired positive indices goals conformity score of the PLET



2.2.4.1 Negative indices

The negative indices here refer to toxic material usage, pollutants emitted, and resource consumption. The basis of evaluation in the area of negative indices is the comparison of the quantity of pollutant emitted with the maximum emission of pollutant type allowed. The quantity of toxic material used and the quantity of non-toxic resource consumed are also compared with the maximum consumption of individual toxic material type and maximum consumption of non-toxic resource type allowed respectively. Under mandatory condition, the comparison of what was achieved is made with what the regulatory authority /law set as allowable limit. Under desired condition, the assessment of negative indices is made in relation to the desired goal set by the firm, industry or by law. In this case, it is not mandatory for the firm to meet the target. However, meeting such target or better performance may give the firm competitive advantage. The negative environmental legislation index can be expressed as:

$$L_{MNIS} = \begin{cases} -1 & \text{if any } (L_{mnir})_{typ} < 0 \\ \dfrac{\sum_{typ=1}^{N_{typ}} (L_{mnir})_{typ}}{N_{typ}} & \text{otherwise} \end{cases}$$

$$(L_{mnir})_{typ} = \left(1 - \frac{q_{pe}}{q_{pa}}\right)_{typ} \qquad (2.33\ a)$$

$$L_{DNIS} = \frac{\sum_{typ=1}^{N_{typ}} (L_{dnir})_{typ}}{N_{typ}}$$

$$(L_{dnir})_{typ} = \left(\frac{L_{niv}}{L_{nig}}\right)_{typ} \qquad (2.33b)$$

where L_{MNIS} Negative legislative score of the PLET under mandatory condition

$(L_{mnir})_{typ}$ Individual negative index rating of the PLET under mandatory condition

$(L_{dnir})_{typ}$ Individual negative index rating of the PLET under desired condition

$(q_{pe})_{typ}$ Quantity of emission of pollutant type or consumption of toxic material type/ resource type *typ* by the PLET

q_{pa} Quantity of emission of pollutant type or consumption of toxic material type/ resource allowed by law

L_{DNIS} Desired negative indices goals conformity score of the PLET

$(L_{niv})_{typ}$ Quantity of emission of pollutant type or consumption of toxic material type/ resource type by the process

$(L_{nig})_{typ}$ Quantity of pollutant type emission or toxic material type/ resource type consumption goal aimed at

2.2.4.2 Positive indices

Positive indices here refer to such attributes as component reuse and product performance standards. Under mandatory condition, the quantity of resource type reuse by the PLET as well as each performance standard type achieved by the PLET is compared with the minimum standard required by law. There are situations where desired targets are set either by legislative authority or at the company level by the management. When meeting the legislative authority set target is not mandatory, it is regarded as desired condition. Thus, positive indices score:

$$L_{MPIS} = \begin{cases} -1 & \text{if any } L_{Pir\,ptyp} < 0 \\ \frac{1}{N_{typ}} \sum_{typ=1}^{N_{typ}} (L_{mpir})_{typ} & \text{otherwise} \end{cases}$$

$$\left(L_{mpir}\right)_{typ} = \begin{cases} -1 & \text{if any } q_{pe} < q_{pa} \\ \left(\dfrac{q_{pe}}{q_{pa}}\right)_{typ} & \text{otherwise} \end{cases} \qquad (2.34a)$$

$$L_{DPIS} = \frac{\sum_{typ=1}^{N_{typ}} \left(L_{dpir}\right)_{typ}}{N_{typ}}$$

$$\left(L_{dpir}\right)_{typ} = \left(\frac{L_{piv}}{L_{pig}}\right)_{typ} \qquad (2.34\ b)$$

where L_{DPIS} Desired positive indices goals conformity score of the PLET

$(L_{mpir})_{typ}$ Individual positive index rating of the PLET under mandatory condition

$(L_{dpir})_{typ}$ Individual positive index rating of the PLET under desired condition

q_{pe} Quantity of components reused or environmental performance standard type achieved

q_{pa} Minimum quantity of components reuse or environmental performance standard type required by law

$(L_{pig})_{typ}$ Quantity of components reuse or value of environmental performance standard type goal aimed at

$(L_{piv})_{typ}$ Quantity of components reuse or value of environmental performance standard type achieved

2.2.5 Environmental attribute

Concern for the environment is fast becoming part of our culture. Although utilisation and end-of-life stages are not the issues that relate environment to manufactured goods, they are significant issues indeed. And, according to Spicer and Johnson [SPJO 98], customers' perception of the environmental importance of end-of-life of product is very high. By extending the life of products, a lot of materials can be diverted from refuse dumps and landfills. It will also result in significant materials and energy savings.

In view of increasing environmental problems such as greenhouse effect, depletion of the ozone layer, acidification, landscape degradation, eutrophication, heavy metals, carcinogens, winter smog, summer smog, pesticides and others, it is clear that the

environment cannot continue to bear an ever-heavier burden. It follows that the environmental impacts of our activities have to be curtailed. Both pollution and resource consumption are forms of impact on the environment. Therefore, the environmental friendliness of each PLET option is evaluated in terms of their resource consumption, waste release, impact of waste released, reduction in resource consumption i.e. resource conserved, and reduction in toxic material content. Figure 2.9 on page 58 shows further details on the constituent elements of environmental attribute. Environmental friendliness of a PLET can therefore be expressed as:

$$
\begin{aligned}
E_{PLET} &= f\,(E_{RCSM}, E_{TMC}, E_{WR}, E_{IWR}, E_{RCSV}, E_{RTMC}) \\
&= E_{RCSM} + E_{WR} + E_{IWR} + E_{RCSV} + E_{RTMC} \\
E_{RCSM} &= E_{NTMC} + E_{TMC} + E_{ELEC} + E_{FUEC} + E_{WTRC} + E_{CAGC} \\
E_{WR} &= E_{SOWR} + E_{LIWR} + E_{GSWR} \\
E_{RCSV} &= E_{MCSV} + E_{ELSV} + E_{FESV} + E_{WTSV} + E_{AGSV}
\end{aligned}
\qquad (2.35)
$$

where E_{PLET} Environmental attribute score of the PLET

E_{RCSM} Resource consumption

E_{TMC} Toxic material content

E_{WR} Waste released

E_{IWR} Waste release impact

E_{RCSV} Resources conserved

E_{RTMC} Toxic material content reduction

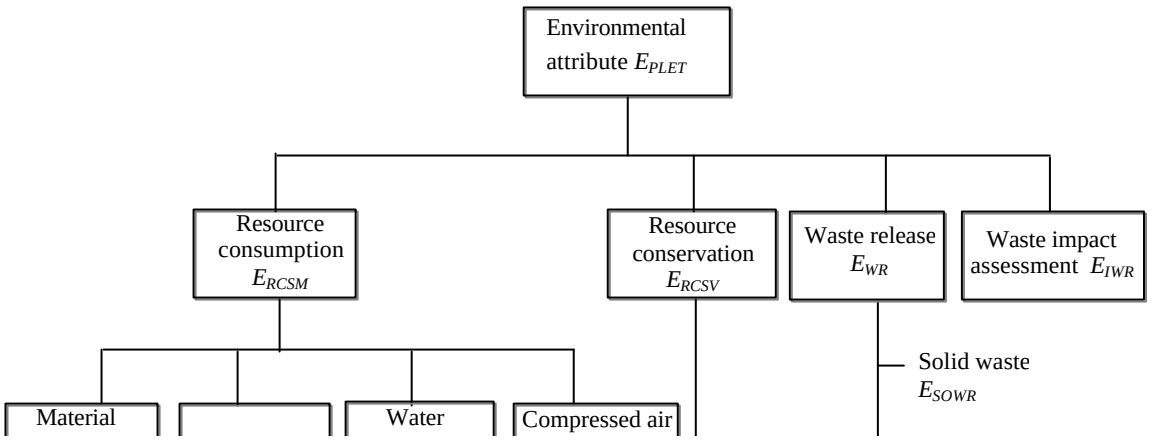
E_{NTMC} Non-toxic material consumption

E_{ELEC} Electrical energy consumption

E_{FUEC} Fuel energy consumption

E_{WTRC} Water consumption

E_{CAGC} Compressed air or gas consumption



Energy
consumption
E_{ECSM}

Energy
conservation
E_{ECSV}

2.2.5.1 Resource consumption

Resource consumption per unit product is calculated by adding the estimated quantity of individual resource type per period and dividing the sum by the number of product reworked by the PLET in the period. This is followed by normalisation across the PLET alternatives to obtain a dimensionless score, which is an indication of environmental friendliness of the PLET with regard to the resource type.

- **Material consumption**

The quantity of materials as well as the toxicity of materials consumed is among the indices used in evaluating the environmental friendliness of a product and process. This module is designed to measure the amount of each material type making up constituent parts of the retired product as well as the replacement parts incorporated into the reworked product. It also considers the amount of individual materials consumed by each process. The toxicity of the material make-up of the retired product as well as that of replacement parts was also assessed. The material types used are thus grouped into toxic- and non-toxic for analysis purpose. The quantity of the 'virgin materials' consumed in the period under consideration for extending the life of the retired product can be obtained from requisitions or estimated from expression 2.36. The material consumption can be obtained from the expression:

$$q_{MC} = \sum_{r=1}^{N_r} (q_{rpp})_r$$

$$q_{rpp} = q_r / N_{rwd} \qquad \text{kg/unit ; l/unit}$$

$$= \quad P\,(1+ L_1 + L_2 + ... + L_n\,) \qquad (2.36)$$

where q_{rpp} Quantity of the non-toxic material type consumed per unit product

q_{pr} Quantity of the material type used per period

N_{rwd} Number of units reworked per period

P Product weight

L Material losses arising from the process used

q_{MC} Total quantity of materials consumed per unit reworked product

r Material type 1, 2, …, N_r (individual materials of in-house made parts are to be included)

- **Toxic materials content**

Just like in the case of non-toxic materials, the quantity of toxic materials content of a product as well as the quantity of toxic materials used for the process per unit product can also be obtained from equation 2.36.

- **Energy consumption**

Energy consumption is also an important index in evaluating the environmental friendliness of a process. There are various sources of energy, namely electricity, solid fuel such as coal; fuel oil such as petrol, diesel, and kerosene, and gases such as natural gas, acetylene, hydrogen. Each of these were assessed in turn and summed up to obtain the energy consumption by the PLET option per product. Electrical energy consumption index involves the evaluation of electrical energy consumption in all its applications in the process of extending the lifecycle of the product. This consists of applications in machinery driving, heating, lighting and other applications. The amount of electrical energy consumed per period can be read from the available measuring device or it can be estimated from the expression 2.37. Machine driving includes energy consumption by electrical energy powered machine tools and other equipment used in the process of extending the product life. Among such machinery are lathe machines, grinding machines, milling machines, drilling machines, welding machines, and conveyors. Heating applications in product life extension may be in separating parts of taken-back products and/or in re-assembling reworked parts.

Electrical energy consumed per period is expressed as:

$$E_{ele} = \sum_{dv=1}^{N_{dv}} (tN_{typ}w)_{dv} \quad \text{kWh /period} \qquad (2.37)$$

$$= t_{ec}(E_{ec}) \quad \text{kWh /period}$$

$$= E_{eler}$$

$$E_{ECV} = 1/N_{rwd}(E_{ele}) \quad \text{kWh/unit}$$

where E_{ECV} Electrical energy consumption per unit product

dv Device type 1, 2, …, N_{dv}

w_{dv} Energy consumption rate by the device/item

$(N_{typ})_{dv}$ Number of type of device dv used in the department

$(t)_{dv}$ Average time duration(hours) of using the device type per period

E_{ele} Electrical consumption in the period under consideration

E_{eler} Electrical consumption per period read from measuring device

E_{ec} Total wattage of all facilities used for reworking the period

N_{rwd} Average number of products reworked in the period under consideration

t_{ec} Estimated number of hours of the period of energy use

Many times, fuel energy is used either as the main source of energy or only for some applications. Different types of fuel such as petroleum products and coal may also be used for different applications. The consumption of such fuel type per period can be obtained from receipts or requisitions made. The quantity of each fuel type consumed per period may also be estimated by using the expression:

$$E_{FECU} = \sum_{flt=1}^{N_{flt}} (E_{FTCU})_{flt} \quad \text{Kg/unit} \qquad (2.38)$$

$$(E_{FTCU})_{flt} = 1/N_{rwd}(E_{flt})$$

$$E_{flt} = \sum_{dv=1}^{N_{dv}} (N_{typ} r_c t)_{dv} \quad \text{Kg per period}$$

where E_{FECU} Fuel energy consumption per unit

$(E_{FTCU})_{typ}$ Fuel energy type consumption per unit product

E_{flt} Quantity of fuel type consumed per period

N_{dv} Number of the types of devices used in the department

$(r_c)_{dv}$ Fuel type consumption rate in Kg/s by the device type

flt Fuel type 1, 2, …, N_{flt}

- **Water consumption**

Water is considered to be one of the most important resources. In product life extension, large quantity of water may be used in cooling or in cleaning. Its consumption per period may be obtained from measuring equipment and the consumption per unit product from the equation:

$$E_{WTRCP} = \frac{q_{wtrc}}{N_{rwd}} \quad \text{Kg/unit} \qquad (2.39)$$

where E_{WTRCP} Water consumption per product

q_{wtrc} Volume of water consumed per period

- **Compressed air consumption**

Compressed air or gas is often used for cleaning. The amount of compressed air or gas used in the period under consideration can also be read from measuring device while the air consumption per product can be obtained from the expression:

$$E_{ARCOSP} = \frac{q_{air}}{N_{rwd}} \text{ Kg/unit} \qquad (2.40)$$

where E_{ARCOSP} Air consumption per product

q_{air} Quantity of air consumed per period

2.2.5.2 Resource conservation/reclamation

Resource conservation arising from using a PLET is in terms of the quantity of individual resources such as materials, energy and water spared by using the process. These can be evaluated as the quantity of virgin resources that would be required to produce new product of the same quality achieved by the PLET less the quantity used in restoring the product by the PLET. Resource conservation score can be evaluated from the expression:

$$E_{RCSV} = E_{MCSV} + E_{ECSV} + E_{WCSV} + E_{ACSV} \qquad (2.41)$$

where E_{RCSV} Resources conserved

E_{MCSV} Materials conservation value

E_{ECSV} Energy conservation value

E_{WCSV} Water conservation value

E_{ACSV} Gas conservation value

- **Material conservation value**

Material conservation value (E_{MCSV}) refers to the amount of materials spared per unit product reworked. It is the amount of materials that would have been consumed in manufacturing new parts but conserved by reusing old components instead of new ones. It is evaluated in terms of individual material type reclaimed per product and is quantifiable from the average weight of parts of the virgin product less the amount consumed per product in that period. Thus the quantity of material type *r* reclaimed per unit-reworked product:

$$E_{MCSV} = \sum_{rrmp=1}^{N_{rrmp}} q_{rrmp}$$

$$q_{rrmp} = q_{rp} - q_{rpp} \quad \text{Kg/unit} \qquad (2.42)$$

where E_{MCSV} Total material conservation value per product

q_{rrmp} Quantity of material type *rrmp* reclaimed per unit reworked product

q_{rp} The amount of the material type required in the production of a unit virgin product

rrmp Raw material type 1, 2,…, N_{rrmp} reclaimed by using the PLET

- **Energy conservation value**

This is the fractional amount of energy that would have been used in manufacturing new parts but conserved by reusing old components instead of new ones. This can be evaluated in terms of the energy types employed from the following expressions:

$$E_{EECSV} = E_{Elerpp} - E_{ECV} \quad \text{kWh/unit}$$

$$E_{FCSV} = E_{Ferpp} - E_{FECU} \quad \text{Kg/unit} \qquad (2.43)$$

where E_{EECSV} Electrical energy conserved per product

E_{FCSV} Quantity of fuel conserved per product

E_{Elerpp} Electric energy required to manufacture a virgin product

E_{Ferpp} Fuel energy required to manufacture a virgin product

- **Water and gas conservation values**

This is the amount of water and gas spared by using the PLET in extending the lifecycle of the product. This can be estimated by using the expressions:

$$E_{WCSV} = E_{Wrpp} - E_{WCSU} \quad \text{Kg/unit} \qquad (2.44a)$$

$$E_{GCSV} = E_{Grpp} - E_{GCSU} \quad \text{Kg/unit} \qquad (2.44b)$$

where E_{WCSV} Quantity of water conserved per product

E_{Wrpp} Quantity of water required to manufacture a virgin product

E_{WCSU} Quantity of water consumed per unit product restored by the PLET

E_{GCSV} Quantity of gas/compressed air conserved per product

E_{Grpp} Quantity of gas/compressed air required to manufacture a virgin product

E_{GCSU} Quantity of gas/compressed air consumed per unit product restored by the PLET

2.2.5.3 Waste release

Emission inventories, whether measured and compiled for point and diffuse sources or conceptually based on emission factors, provide data on the potential effects. These in conjunction with dispersion models and data on critical loads or human responses can be used to provide early warnings of potential hazardous situations. The inadequacy of the existing data collections and current analytical methods to meet the information needs of the decision-makers has led to the development of environmental indicators. This is a short hand method of examining environmental situations in a manner readily understandable by experts and the public [UNEP 94]. The environmental indicators developed in this work are performance indicators for evaluating product life extension processes.

Industrial processes are among the sources waste releases. Although each of the product life extension processes will release waste, but the quantity and the form of waste generated by each of them will vary because of the differences in the constituent operations and variation in the depth of operations involved. Cleaning, disassembly, reconditioning, part

manufacturing and reassembly operations of PLET are the main sources of solid waste generations from which scraps, dusts, chips and other forms of solids wastes are produced. Majority of the liquid effluents discharged in PLET is made up of particle washout from cleaning operation, Spills of coolants and other fluids used in PLETs. These are generally computed as the product of an activity level i.e. a measure of the type and scale of an anthropogenic source, e.g. machining and an emissions factor. The common types of gaseous emissions considered are nitrogen oxides (NO_x), sulphur dioxide (SO_2), carbon dioxide (CO_2), hydrogen sulphide (H_2S), ammonia (NH_3), ethene (C_2H_4), methane (CH_4) and particulate. Quantity of waste released can be obtained from the equation:

$$
\begin{aligned}
E_{WR} &= f(N_{op}, d_{op}) \\
&= E_{SWGFP} + E_{LEDFP} + E_{GSEFP} \quad \text{Kg/unit} \\
E_{SWGFP} &= \frac{\sum_{op=1}^{N_{op}} (q_{wst})_{op}}{N_{rwd}} \quad \text{Kg/unit} \\
E_{LEDFP} &= \frac{d_{effl} \sum_{op=1}^{N_{op}} (v_{effl})_{op}}{N_{rwd}} \quad \text{Kg/unit} \\
E_{GSEFP} &= \frac{d_{gsem} \sum_{op=1}^{N_{op}} (v_{gsem})_{op}}{N_{rwd}} \quad \text{Kg/unit} \qquad (2.45)
\end{aligned}
$$

where

op	PLET operation 1,2, …, N_{op}
d_{op}	Degree of the operations' intensity
E_{WR}	Total quantity of waste generated per product
E_{SWGFP}	Quantity of solid waste generated from the process per product
E_{LEDFP}	Liquid effluents discharged from the process per product
E_{GSEFP}	Quantity of gas emitted per unit product
q_{wst}	Quantity of solid waste generated by the process per period
v_{effl}	Volume of liquid effluents discharged per period
δ_{effl}	Density of the liquid effluent
v_{gsem}	Volume of gases emitted per period
δ_{gsem}	Density of the gases emitted

2.2.5.4 Waste Impact Assessment

Environmental impacts of industrial activities include greenhouse effect, ozone layer depletion, acidification, landscape degradation and eutrophication. The extent of manifestation of these impacts depends on the amount of waste and toxicity of waste. Other factors affecting environmental impact of pollutants are: bioavailability, toxicity, route of exposure, dose, duration of exposure, the form in which the pollutant occurs, reaction and interaction, and sensitivity [POGR 93, MHWA 93]. Environmental impact assessment evaluates the degree of potential harm to be expected from the substances emitted by the process. Environmental impacts of processes can be quantified through the use of instrumentation, data acquisition and application of models or other acceptable quantification techniques. In situation where quantitative measurements are not possible, qualitative measurements may be used. Each of the emitted waste constituents has impact and the intensity/degree of impact on the environment varies. The impact may be at the local/factory level, in the region of emission, or at the global level. According to SETAC, impact assessment procedure consists of classification and characterisation, normalisation, and evaluation [PREC 97]. In this work environmental impact of the PLET options are evaluated in terms of the nearness of constituent element (such as SO_2) emitted to the threshold value of the constituent element. Thus waste release impact can be computed as:

$$E_{IMAS} = f(E_{WR}, tx_{WR}) \tag{2.46}$$

$$= \begin{cases} \dfrac{1}{N_{wcst}} \displaystyle\sum_{wcst=1}^{N_{wcst}} \left(\dfrac{\displaystyle\sum_{op=1}^{N_{op}} (q_{wcst})_{op} - LD_{50}}{LD_{50}} \right)_{wcst} & \text{If all } \displaystyle\sum_{op=1}^{N_{op}} (q_{wcst})_{op} \le LD_{50} \text{ for each } wcst \\ 1 & \text{If any } \displaystyle\sum_{op=1}^{N_{op}} (q_{wcst})_{op} > LD_{50} \text{ for each } wcst \end{cases}$$

where E_{WR} Amount of waste

tx_{WR} Toxicity of waste

E_{IMAS} Waste impact assessment index /Environmental impact indicator

$wcst$ Waste constituent type 1, 2,…, N_{wcst}

$(q_{wcst})_{op}$ Quantity of the waste constituent type generated by the specific

operation

LD_{50} Lethal dose of the waste constituent type

When $E_{IMAS} < 0$, it means the waste released by the PLET has no negative environmental impact while $E_{IMAS} \geq 0$ means the waste emitted has negative environmental impact. Waste release impact score E_{IWR} is the value obtained after normalising the PLETs' impact assessment indices.

2.2.5.5 Reduction in toxic materials content

Reduction in toxic materials consumption is also seen in this worked as an index of environmental friendliness of a process. It can be estimated from the expression:

$$E_{RTMC} = q(_{tmc})_{fp} - q(_{tmc})_{rwd} \quad (2.47)$$

where $q(_{tmc})_{fp}$ Quantity of toxic materials needed for the production of a unit virgin product

$q(_{tmc})_{rwd}$ Quantity of toxic materials required for reprocessing a unit product

2.2.6 Technical attribute

Technical attribute is used in this work to refer to a group of factors concerned with the technical ground upon which the choice of a PLET should be based to achieve the desired functional quality. Figure 2.10 (on page 69) shows the constituent elements of the technical attribute considered relevant for this scenario. The technical suitability of the PLET is evaluated by the assessment of the product, the process as well as the infrastructural facilities available for use. Technical suitability can generally be expressed as:

$$T_{PLET} = f(T_{PDCD}, T_{PDCF}, T_{PCXT}, T_{TCAP})$$
$$= T_{PDXT} + T_{PCXT} + T_{TCAP} \quad (2.48)$$

where T_{PDCD} Product condition

T_{PDCF} Product configuration

T_{PCXT} Process characteristics

T_{TCAP} Techno-capability

2.2.6.1 Product Characteristics (T_{PDXT})

This sub-technical module assesses the nature of the product in its present state in correlation with the PLET option. It evaluates the complexity of the product configuration and the product condition, and attempts to determine how this affects the PLET option. Product complexity factor assesses the difficulty involved in processing the product on the basis of its structure to meet indicated functional quality achievable under specific PLET option. This factor is a function of the variety and sizes of liaisons, geometric configuration of the parts as well as the material variety used. Product condition factor evaluates the extent of product deterioration before being brought for rework in terms of being reworkable and still meeting PLET quality specifications. This module is thus aimed at identifying the most suitable PLET option under the prevailing product condition. The product characteristics score with regard to PLET selection can therefore be evaluated from the expression:

$$T_{PDXT} = T_{CXS} + T_{PDCD} \qquad (2.49)$$

$T_{CXS} \in [0, 1]$ (choose from Table 2.14)

$T_{PDCD} \in [0, 1]$ (choose from Table 2.15)

where T_{CXS} Product complexity score

T_{PDCD} Product condition score

Product complexity	Complexity score T_{CXS}
Very high	0.1
High	0.3
Average	0.5
Simple	0.7
Very simple	0.9

Table 2.14: Product complexity rating with regard to ease of handling by the PLET option

Product condition	Suitability	Condition score T_{PDCD}
Very bad	Absolutely unsuitable	0.1
Bad	Unsuitable	0.3
Average	Manageable	0.5
Good	Acceptable	0.7

Very good	Perfect	0.9

Table 2.15: Product condition score with regard to its suitability for the PLET option

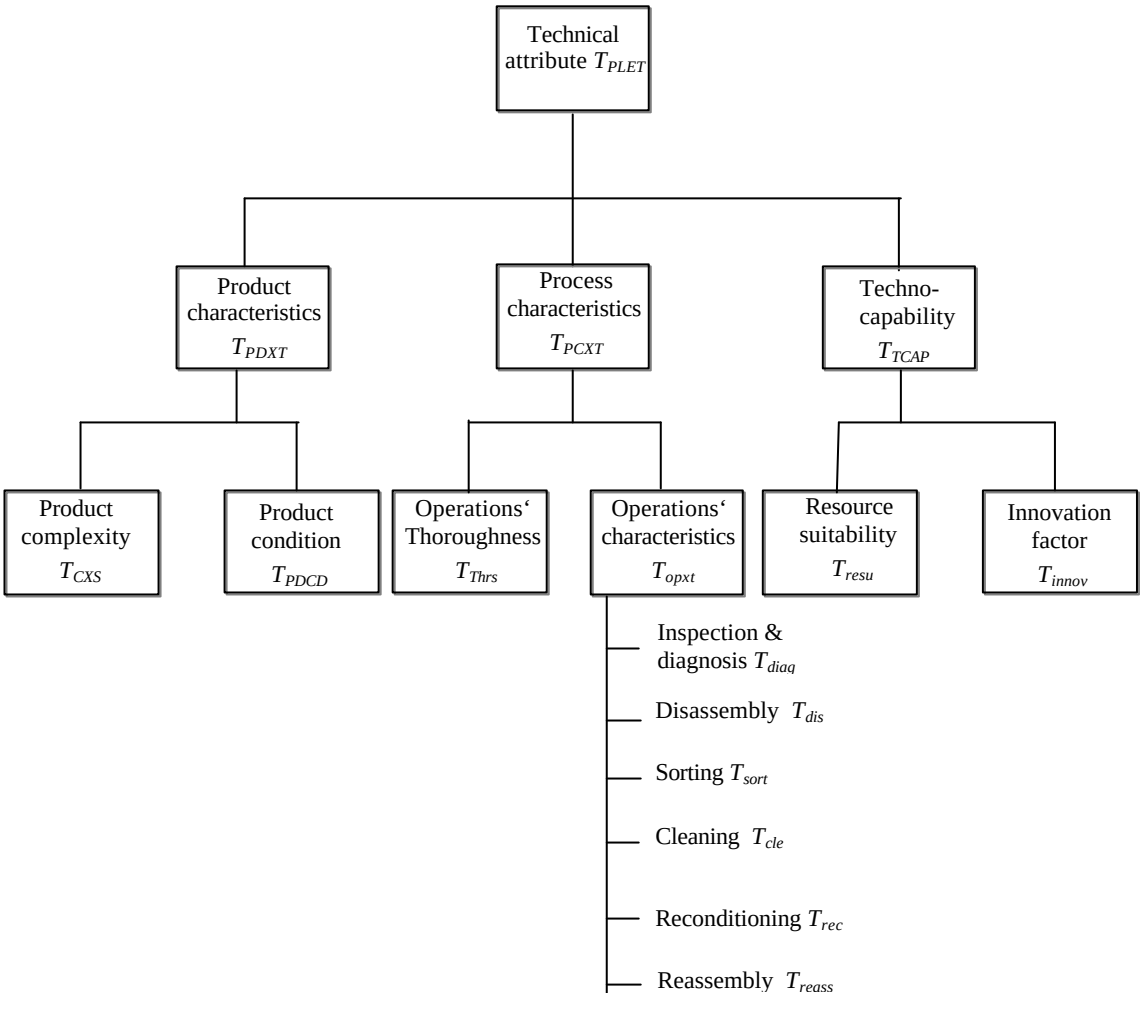
2.1.6.2 Process Characteristics (T_{PDXT})

This sub-attribute measures the extent of effort involved in the use of individual PLET option in terms of its constituent operations and the required thoroughness of each operation. Thoroughness sub-sub-attribute assesses the depth of treatment required in each operation making up the PLET option in order to meet the required standard. This factor affects the process time and the consequent PLET option cost per product:

$$T_{Thrs} = \frac{1}{N_{op}} \sum_{op=1}^{N_{op}} (T_{Thrr})_{op} \tag{2.50}$$

where T_{Thrs} Thoroughness score of the PLET option

$(T_{Thrr})_{op}$ The rating of required thoroughness of the PLET option's operation (use Table 2.16)



Thoroughness requirement	Thoroughness rating $(T_{Thrr})_{op}$
Very high	0.1
High	0.3
Average	0.5
Simple	0.7
Very simple to none	0.9

Table 2.16: Thoroughness requirement rating

Operations characteristics sub-module assesses how much volume of each of the PLET activities has to be carried out to achieve the quality standard expected from the PLET option. With regard to inspection and diagnosis, almost all the PLET options require the diagnosis of the product condition at the point of coming to the factory. This section evaluates the extent of diagnosis required by the PLET option. This is relevant as it affects the extent of diagnostic equipment- and personnel requirement to assess the extent of damage and to estimate the required treatment to bring the product to necessary functional quality. It is subjectively measured using Table 2.17.

$$T_{dags} \in [0, 1] \quad \text{(choose from Table 2.17)} \tag{2.51}$$

where T_{dags} Inspection and diagnosis score

Required diagnostic intensity	Diagnosis score T_{dags}
Very high	0.1
High	0.3
Average	0.5
Simple	0.7
Very simple to no diagnosis	0.9

Table 2.17: Diagnosis intensity requirement and rating

Disassembly is the process whereby used products can be efficiently taken apart [BANA 95]. This section measures the extent of disassembly required by the PLET option and thereby evaluates the ease with which the PLET option can be carried out with regard to parts dismantling. This factor is basically dependent on the ease with which the connectors used in assembling the parts can be dissolved. The table below groups and rates common connector types used in mechanical product assembly according to their ease of dissolution. The disassembly score can then be calculated from the expression:

$$T_{diss} = (T_{disrr})(T_{eods}) \quad (2.52)$$

$$T_{eods} = \frac{1}{N_{ltyp}} \sum_{ltyp=1}^{N_{ltyp}} (N_l T_{eodrl})_{ltyp} \quad (2.53)$$

where T_{diss} Disassembly score

T_{eods} Ease of dissolution score

N_{ltyp} Number of variety of liaisons

N_l Number or quantity of the specific type of liaisons

T_{eodrl} Ease of liaison dissolution rating (choose from Table 2.18)

l Liaisons, also referred to as connectors

T_{disrr} Disassembly requirement rating (choose from Table 2.19)

Liaisons/connectors	**Ease of dissolution rating** T_{eodrl}
Slips, pins (clevis-pin, cotter-pin, spring/roll pin, spiral/coiled spring pin, taper pin, dowel pins, grooved pins, quick-release pins), plug and retainers	0.95
Bolts, screws, nuts and washers	0.80
Snap fits, press fits	0.65
Rivet	0.50
Adhesives	0.35
Spot welding	0.20
Soldering, brazing and welding	0.05

Table 2.18: Liaison dissolubility rating

Required disassembly intensity rdi		**Disassembly requirement rating** T_{disrr}
Complete	(rdi =100%)	0.1
High	(65% ≤ rdi < 100%)	0.3
Average	(45% ≤ rdi < 65%)	0.5
Little	(25% ≤ rdi < 45%)	0.7

Very little	(rdi < 25%)	0.9

Table 2.19: Disassembly requirement rating

Sorting sub-attribute evaluates the degree of technicality required to sort the disassembled products into different parts and groups. It is evaluated in terms of the number of methods that has to be combined to effectively sort them. The score can be evaluated from:

$$T_{sorts} = \frac{1}{N_{somd}} \sum_{somd=1}^{N_{somd}} (T_{efr})_{somd} \qquad (2.54)$$

where T_{sorts} Sorting score

N_{somd} Number of sorting methods combined/utilised

$(T_{efr})_{somd}$ Effectiveness of the sorting method in separating the product parts

Sorting method effectiveness	**Effectiveness rating** $(T_{efr})_{somd}$
Very high	0.9
High	0.7
Average	0.5
Low	0.3
Very low	0.1

Table 2.20 Sorting method effectiveness rating

Cleaning score evaluates the intricacy of cleaning required by the product with respect to the PLET option. A number of methods are commonly used for cleaning. These include spraying, high pressure spraying, immersion, fat removal by condensation, flooding, injective flooding, blowing and compressed air blowing, as well as ultrasound cleaning [STHU 93]. Others include abrasive cleaning, especially surface grinding which are frequently used in practice. In addition to a number of conditions such as temperature, pH value of the medium used whether acidic or basic, pressure and motion which may be employed, a cleaning operation may combine two or more of earlier mentioned methods before being able to achieve the desired level of cleaning. However, application of any of these is subject to a number of factors, namely, product characteristics, nature of the dirts and differences between the dirts. Scoring the PLET options with regard to cleaning is a function of the required cleaning quality, the number of components to be cleaned, the nature of the contamination to be removed, available methods of cleaning, impact of each method on the product material, and effectiveness of the method in removing the

contamination. Conformity of the method to legislative control, energy requirement, water and other resources consumption, emissions and waste releases are other considerations in evaluating cleaning operation. Cleaning operation score can thus be calculated from the expression:

$$T_{cles} = \frac{1}{N_{clmd}} \sum_{clmd=1}^{N_{clmd}} (T_{efr} + T_{impr})_{clmd} \quad (2.55)$$

where T_{cles} Cleaning score

N_{clmd} Number of cleaning methods 'combinedly' utilised

$(T_{efr})_{clmd}$ Effectiveness of the cleaning method in cleaning the product parts (choose from Table 2.21)

$(T_{impr})_{clmd}$ Impact rating of the cleaning method (choose from Table 2.22)

Effectiveness assessment	**Effectiveness rating T_{efr}**
Very high	1.00
High	0.75
Average	0.50
Low	0.30
Very low	0.10
Ineffective	0.00

Table 2.21: Effectiveness rating of methods employed in carrying out an operation

Negative Impact of the method on the product	**Impact rating T_{impr}**
None	1.00
Very little	0.82
Little	0.64
Medium	0.46
High	0.28
Very high	0.10

Table 2.22: Impact rating of methods employed in carrying out an operation

Reconditioning factor evaluates the amount of efforts required to achieve the functional quality demanded of the restored product as dictated by the choice of the PLET option. It considered both the effectiveness and impact of various methods employed in achieving the desired goal.

$$T_{rec} = T_{recrr}\left[\frac{1}{N_{recmd}}\sum_{recmd=1}^{N_{recmd}}(T_{efr} + T_{imp})_{recmd}\right] \quad (2.56)$$

where T_{rec} Reconditioning score of the PLET,

N_{recmd} Number of reconditioning methods combined

$(T_{efr})_{recmd}$ Effectiveness of the reconditioning method in correcting the fault of the part (choose from Table 2.21)

$(T_{imp})_{recmd}$ Impact rating of the reconditioning method(s) on the part and/or liaison (choose from Table 2.22)

T_{recrr} Required reconditioning rating of parts and liaisons (choose from Table 2.23 on page 75)

Required reconditioning intensity *rreci*		**Reconditioning requirement rating** T_{recrr}
Complete	(rdi =100%)	0.1
High	(65% ≤ rdi < 100%)	0.3
Average	(45% ≤ rdi < 65%)	0.5
Little	(25% ≤ rdi < 45%)	0.7
Very little	(rdi < 25%)	0.9

Table 2.23: Reconditioning requirement rating

Reassembly factor assesses the ease of reassembling the parts and the liaisons reworked as a whole. Dimensionless substances such as lubricants, adhesives, etc. can be applied additionally. Re-assembly operations can be divided into two basic categories, namely: parts mating and parts joining. Parts mating involve bringing of two or more parts into contact with each other while parts joining involve the application of a fastening procedure to hold the mated parts together so that they can maintain their relationship with each other. Some of the classes of commonly used classes of connectors are shown in Table 2.18. Qualitative assessment of the reassembly operation of a PLET alternative is similar to disassembly operation, except that the parts and connectors condition is not relevant, because they are expected to have been put right. However, usage of easier or better joining method especially for replaced parts and subassemblies was considered. Thus in differentiating between PLET alternatives, the number of joints worked, ease of assembly rating of the joining method, variety of the joints and quality of the work involved in terms of ease of reassemblability and reusability were assessed. Reassembly score can be expressed as:

$$T_{reass} = (T_{rerr})(R_v) \quad (2.57)$$

$$R_v = \frac{1}{N_{voj}} \sum_{jt=1}^{N_{jt}} \frac{N_{rjt}}{N_{jt}} \left(\frac{T_{eorr} + T_{rurp}}{2} \right)_{jt} \quad (2.58)$$

where T_{reas} Reassembly score

R_v Reassemblability

T_{eorr} Ease of reassembly rating of the joint/part/fastener type jt $_{jt=1, 2,..., N}$ (choose from Table 2.24 on page 75)

T_{rurp} Reusability rating of the joint/part/fastener jt $_{jt=1, 2,..., N}$ (choose from Table 2.25 on page 75)

N_{voj} Variety of joints or number of different joint types

N_{rjt} Average number of reusable matings/joints per product

N_{jt} Total number of matings/joints per product

T_{rerr} Reassembly requirement rating of the product (choose from Table 2.26)

Liaisons	**Ease of reassemblability rating** T_{eorr}
Rivet	0.95
Clips, pins, plug and retainers	0.80
Bolts, screws, nuts and washers	0.75
Snap fits, press fits	0.65
Spot welding	0.35
Adhesives	0.20
Soldering, brazing and welding	0.05

Table 2.24: Liaison reassemblability rating

Parts and liaisons	**Reuseability rating** T_{rurp}
Both parts of the joint and the liaisons are reusable without rework	1.00
The parts are reusable without rework and the liaisons reusable with minor rework	0.85
Only the two parts of the joint are reusable without rework	0.70
One part is reusable without rework and the other part reusable after some rework	0.50
Only one of the parts of the joint are reusable without rework	0.30
Only one part is reusable after some rework	0.10
No part is reusable	0.00

Table 2.25: Reuseability rating of parts to a joint

Required reassembly intensity rri		**Reassembly requirement rating** T_{rerr}
Complete	(rri =100%)	0.1
High	(65% ≤ rri < 100%)	0.3
Average	(45% ≤ rri < 65%)	0.5

Little	($25\% \leq rri < 45\%$)	0.7
Very little	($rri < 25\%$)	0.9

Table 2.26: Reassembly requirement rating

Testing operation is concerned with verifying the quality such as durability of the reprocessed product. Just like in the case of diagnosis, this index evaluates the difficulty involved in assessing the quality of the reworked product. The evaluation is made in terms of the number of tools required and the impact of each test on the product, whether it is destructive or non-destructive. The testing score is thus obtainable from the expression:

$$T_{tess} = \frac{1}{N_{\text{mod}}} \sum_{\text{mod}=1}^{N_{\text{mod}}} \left(\frac{1}{N_{tesmd}} \sum_{tesmd=1}^{N_{tesmd}} (T_{efr} + T_{imp})_{tesmd} \right)_{\text{mod}} \quad (2.59)$$

where N_{tesmd} Number of test methods combined/utilised

$(T_{imp})_{tesmd}$ Impact rating of the test method(s) on the part (choose from Table 2.22 on page 74)

$(T_{efr})_{tesmd}$ Effectiveness of the test method in assessing the performance quality of the part/module/product (choose from Table 2.21 on page 74)

mod Functional modules

Packaging score is the last operation in some of the PLET options such as remanufacturing. Good packaging can reduce the amount of damaged product, thereby reducing the cost of the loss of that product, remanufacturing cost and loss of reputation which comes with damaged product [BANA 95, YAMB 96a]. This sub-module evaluates the extent of work involved and the impact of the work on the product. Therefore, the packaging score:

$$T_{pacs} = \frac{1}{N_{mtd}} \sum_{mtd=1}^{N_{mtd}} (T_{pacr})_{mtd} \quad (2.60)$$

where N_{mtd} Number of methods used/making up the packaging operation

T_{pacr} Packaging method rating (choose from Table 2.27 on page 77)

mtd Methods

In summary, the PLETs total operations score is given by the expression:

$$T_{opxt} = \sum_{ops=1}^{N_{ops}} T_{ops} \tag{2.61}$$

where T_{ops} Individual operation's score

T_{opxt} The PLET's total operations score

The process characteristics score of the PLET is then given by the expression:

$$T_{PCXT} = T_{Thrs} + T_{opxt} \tag{2.62}$$

Packaging method	Packaging method rating T_{pacr}
Very good	0.9
Good	0.7
Average	0.5
Below average	0.3
Unacceptable	0.1

Table 2.27: Packing method rating

2.2.6.3 Techno-capability factor (T_{TCAP})

Techno-capability factor evaluates both the suitability of available resources for the PLET and the extent of product innovation resulting from the process in comparison with the substitutes. The resource suitability sub-sub-attribute assesses the level of availability of such resources like manpower, machinery, energy, water, and others with the aim of evaluating their adequacy for the PLET option. This factor considers on-the-site availability, as well as quantitative and qualitative adequacy of available resources. Innovation index assesses the degree of innovation 'inputed' into the PLET finished product from the technology available to the firm in comparison with the competitors. If the importance of the innovation type is not zero for any type of innovation type, then innovation score can be evaluated from the expression:

$$T_{TCAP} = T_{resu} + T_{inos} \tag{2.63}$$

$$T_{resu} = \frac{1}{N_{resutyp}} \sum_{resutyp=1}^{N_{resutyp}} \left(T_{resr}\right)_{typ}$$

$$T_{inos} = \begin{cases} \dfrac{1}{N_{inovtyp}} \displaystyle\sum_{innovtyp=1}^{N_{inovtyp}} \left(\dfrac{(T_{dirinov})(T_{inovrPLET})}{T_{inovr\,cp}} \right)_{typ} & \text{for all } T_{diriinov} \neq 0 \\ 0 & \text{otherwise} \end{cases}$$

where T_{resu} Resource suitability score

$T_{resrtyp}$ The suitability rating of the resource type (choose from Table 2.28)

$N_{resutyp}$ Number of resource types considered

$T_{inovrPLET}$ Product´s innovation/novelty type rating (choose from Table 2.29 on page 78)

$T_{inovrcp}$ Competitor´s product innovation type rating (choose from Table 2.29 on page 78)

$N_{inovtyp}$ Number of innovation/novelty types considered

$T_{dirinov}$ The degree of importance/relevance of the innovation/novelty type (choose from Table 2.30)

If	then it is	Suitability rating T_{resr}
$T_p \geq T_r$	good	0.9
$T_p < T_r$ but there is T_{af}	fair	0.5
$T_p < T_r$ but there is unaffordable T_{av}	bad	0.1
$T_p < T_r$ but there is no T_{av}	impossible	0.0

Table 2.28 Techno-availability/suitability status ratings

where T_p Level of resource type possessed by the firm

T_r Level of resource type requirement by alternative *j*

T_{av} Level of resource type that meets the requirement of alternative *j* and is available in the region of the firm for purchase

T_{af} Level of resource type that meets the requirement of alternative *j* and is available in the region of the firm which the firm can afford to pay for

Degree of innovation involved	Innovation rating T_{inovr}
Very high	0.9
High	0.7
Average	0.5
Little	0.3
Very little	0.1

Table 2.29: Product innovation rating

Degree of importance/relevance of the innovation to the consumer/product performance	**Innovation rating** $T_{dirinov}$
Very high	0.9
High	0.7
Average	0.5
Little	0.3
Very little	0.1

Table 2.30: Importance/relevance rating of the product innovation type

2.3 Minimum standard on attributes

After the identification of all attributes that are essential to make adequate decision, it is necessary to establish a baseline for process requirements and goals. Thus, an acceptable PLET must meet minimum standard on cost, market, time, legislative, environmental and technical attributes. These standards set by this work are generalised minimum standards. These may have to be adjusted for each decision situation. The specific minimum standard for a decision situation depends on the product factors P_{ft}, the decision maker D_m, and locational factors l_{ft}).

$$S_{MIN} = f(P_{ft}, D_m, l_{ft}) \quad (2.64)$$

where S_{MIN} Minimum standard for an attribute

2.3.1 Minimum standard on cost attribute

This is the maximum cost allowable for any of the PLET option to be acceptable. One of the following two conditions can be set as minimum standard condition on cost attribute. The two conditions are profitability- and disposal cost based conditions. Under profitability-based condition, for any PLET to be acceptable, its estimated implementation cost must not be higher than the expected market value of the PLET reworked product. This is the cost that allowed for profitability in the PLET execution. This standard is recommended for firms that are not under mandatory legislative obligation to carry out PLE. A variant of this involve iteratively setting maximum allowable departmental cost such that the profitability goal may be reached. The term “value” used here refers to monetary values in each case. The material conservation value is used here to mean the monetary value of material

constituents of the retired product. The value of the virgin materials is here used, with the depreciation factor taking care of the deteriorated condition of the retired product.

- **Profitability condition**

$$V_{RWDP} \geq C_{PLET}$$
$$G_{PLET} = V_{RWDP} - C_{PLET}$$
$$V_{RWDP} = (V_{MCSV})\,(D_p) + V_{RCSV} \qquad (2.65a)$$

- **Allowable departmental/operational cost**

$$C_{PLET} \not> \sum_{op=1}^{N} (C_{\max})_{op} \qquad (2.65b)$$

where V_{RWDP} Reclaimed product value [2]

C_{PLET} Cost of using the process

$(C_{max})_{op}$ Maximum allowable cost for the operation/department

G_{PLET} Profit/gain margin accrued from the reworked product due to using the process

V_{MCSV} Materials conservation value

E_{OCSV} Other resources conserved

D_p Depreciation factor

- **Disposal condition**

Under disposal cost based condition, the PLET cost must at least be lower than the disposal cost even if the profitability condition is not met. This condition should be acceptable to firms under mandatory legislative obligation of taking back their product. The only exception under which PLET cost being the same as disposal cost can be acceptable is when the firm prized the corporate goodwill attached to being “green” than monetary gain. However, the PLET cost should not be more than the disposal cost. This can be written as:

$$C_{PLET} \leq C_{DSP} \qquad (2.66)$$

where C_{PLET} Cost of using the process

C_{DSP} Disposal cost

2.3.2 Minimum standard on market attribute

The performance of each PLET is evaluated in terms of major market elements such as supply quantity, supply quality, demand quantity and demand quality. The quantitative and qualitative availability of the retired product as well as all supportive materials required to rework the product must be adequate enough to meet the reworked product quality, satisfy operating capacity and provide for no financial loss. The quality of reworked product turned out by the PLET must meet the market standard and the demand for the reworked product must be large and stable enough to ensure continual existence of the firm. This can be expressed as:

$$(M_{SQT} + M_{SQL} + M_{DQT} + M_{DQL})_{PLET} \geq (M_{SQT} + M_{SQL} + M_{DQT} + M_{DQL})_{MIN} \quad (2.67)$$

2.3.3 Minimum standard on time attribute

A PLET option is only acceptable if the required time to carryout the PLET that meets the required quality standard and the set delivery time by the customer (s) agree. This is particularly relevant to custom production mode. If there is no set delivery time requirement from the customer, effort could be made to the reduce the process time per unit reworked product by setting time limits for some operations and other sub-time attributes. Thereby cutting the direct labour cost, machinery utilisation cost and energy cost. These standards can be written as:

$$\begin{aligned} t_{PLET} &\leq t_{CST} \\ &\leq t_{MALD} \\ t_{MALD} &= \sum_{op=1}^{N_{op}} (t_{mald})_{op} + (t_{DET} + t_{AUX})_{mald} \end{aligned} \quad (2.68)$$

where t_{CST} Customer set time

t_{MALD} Maximum allowable reprocessing time per unit reworked product

$(t_{mald})_{op}$ Maximum allowable time for the specific operation

$(t_{DET})_{mald}$ Maximum allowable delay time

$(t_{AUX})_{mald}$ Maximum allowable auxiliary time

[2] Reclaimed product value is the price at which the reclaimed product will sell on the market. It can alternatively be estimated as the sum of the reclaimed product material value (at its depreciation level) and the value of resources spared by reclaiming rather than working the material from the scratch.

2.3.4 Minimum standard on legislative attribute

The minimum standard on legislative attribute is meeting the mandatory environmental regulations. Inotherwords, all activities being carried out from the gathering aspect of the pre-treatment logistics to the sales of reprocessed product must conform to all mandatory environmental regulations. This can be expressed as:

$$L_{PLET} \geq (L_{MNIS} + L_{MPIS}) \tag{2.69}$$

where L_{PLET} Legislative attribute score

L_{MNIS} Sum of mandatory negative sub-legislative attributes scores

L_{MPIS} Sum of mandatory positive sub-legislative attributes scores

2.3.5 Minimum standard on environmental attribute

The minimum performance standard in this case is either the one set by the industry to which the firm belongs, by law or by the firm itself. The performance of each PLET is evaluated in terms of individual environmental elements such as resource consumption, toxic material content, resource conservation, waste release and environmental impact of waste released, as well as reduction in toxic material content. The PLET is acceptable only if its value is greater or equal to the minimum standard of positive environmental indicators and smaller than maximum allowable negative environmental indicators. Positive environmental indicators are individual resources conserved by carrying out PLE and reduction in toxic material content of the product. Negative environmental indices consist of individual item making up resource consumption, wastes released and environmental impact. For PLET to be acceptable:

$$(E_{pei})_{PLET} \geq (E_{pei})_{MIN} \quad \text{and} \quad (E_{nei})_{PLET} < (E_{nei})_{MAX} \tag{2.70}$$

2.3.6 Minimum standard on technical attribute

Technical feasibility of extending the lifecycle of a product hangs mainly on the product condition and suitability of available resources. The condition of the product must be that which permits product rework such that the reworked product will meet the functional quality requirement for a set period without any fault. The available resources must also be suitable for handling the product such that the least functional quality requirement will be met. When any of these two conditions are not met, the life of the product cannot be

extended. Thus, the available resource capability must be compared with required resource capability. Similarly, average product condition must be compared with conditions suitable for each of the PLET options. This can be written as:

$$[T_{PDXT} + T_{TCAP}]_{PLET} \geq [T_{PDXT} + T_{TCAP}]_{MIN} \quad (2.71)$$

where $[T_{PDXT}]_{PLET}$ Product characteristic score of the PLET

$[T_{TCAP}]_{PLET}$ Techno-capability score of the PLET

$[T_{PDXT}]_{MIN}$ Required minimum product characteristic score

$[T_{TCAP}]_{MIN}$ Required minimum techno-capability score

In other words, the retired product condition must at least be manageable for the PLET option such that the reworked product meets the required quality standard for a set techno-economic life and the available infrastructure must be suitable for the PLET. From Tables 2.15 and 2.28, it means that the product condition and the available resources suitability with regard to the PLET must be:

$$[T_{PDXT}]_{PLET} \geq 0.5 \leq [T_{TCAP}]_{PLET} \quad (2.72)$$

The minimum standards to be fulfilled before any PLET can be acceptable for use in extending the lifecycle of a product may be summed up as:

$$\left\{\sum_{j=1}^{N_j} w_j v(f_j)\right\}_{\min} = \sum_{j=1}^{6} w_j v(S_{MIN})_j \quad (2.73)$$

In this case

$$(S_{MIN})_1 = \begin{cases} V_{RWDP} & \text{if the cost standard is profitability based} \\ C_{DSP} & \text{if the cost standard is based on disposal cost} \end{cases}$$

$$(S_{MIN})_2 = (M_{SQT} + M_{SQL} + M_{DQT} + M_{DQL})_{MIN}$$

$$(S_{MIN})_3 = \begin{cases} t_{CST} & \text{if the time standard is based on customer set delivery time} \\ t_{MALD} & \text{if the standard is based on maximum allowable time on operations} \end{cases}$$

$$(S_{MIN})_4 = (L_{MNIS} + L_{MPIS})$$
$$(S_{MIN})_5 = (E_{pei})_{MIN} + (E_{nei})_{MAX}$$
$$(S_{MIN})_6 = [T_{PDXT} + T_{TCAP}]_{MIN}$$

where $(S_{MIN})_1$ Minimum standard on cost attribute

$(S_{MIN})_2$ Minimum standard on market attribute

$(S_{MIN})_3$ Minimum standard on time attribute

$(S_{MIN})_4$ Minimum standard on legislative attribute

$(S_{MIN})_5$ Minimum standard on environmental attribute

$(S_{MIN})_6$ Minimum standard on technical attribute

2.4 Weighting evaluation criteria

Each attribute needs a weighting factor to determine the relative importance in the final value of a potential process alternative [SPBU 94]. This information as to the relative importance of each attribute to the decision problem is particularly required when using some decision-making methods like simple additive weighting method [HWYO 81]. Among the numerical formula methods for assigning weights are uniform or equal weights, rank sum weights and rank reciprocal weights. For detailed information on methods of assigning preference weights, [HWYO 81; CHHW 92, SUCA 92] should be consulted.

Although the formula methods for assigning weights are easy to use but they are less defensible than direct assignment of weights, which are based on preference comparisons among criteria. For this reason, direct assignment of weights is used in this work. However, whatever method is used, the preference weights have to be normalised so that:

$$\sum_{i=1}^{m} w_i = 1, \qquad 0 \le w_i \le 1$$

Having identified and analysed the decision attributes, and determined the acceptable limit on each attribute upon which process alternatives evaluation are to be based, the next step is to identify the process alternatives. This, i.e. alternative identification and assessment, and sensitivity analysis as well as alternative selection will be discussed in chapter 3.

3. The PLET Selection Model

3.1 PLET Alternatives Identification

The quality and quantity of reprocessed product output decisions define the choice of PLET. Stahel and Jackson, and Andreu [STJA 93, ANDR 97] identified a number of process alternatives for product recovery. The five notable ones among these product life extension techniques are repair and maintenance, refurbishing; remanufacturing; upgrading, and cascading. The identification of each of these PLETs is initiated by functional level breakdown and flow block analysis. It is followed by the assessment of resource requirements of each PLET operation, and the data resulting from these are used to evaluate the suitability of the PLET option. Figure 3.1 shows the lifecycle stages at which the product life extension takes place and various methods by which the life of a product can be extended.

Owing to possibility of variation in what constitute a PLE process option from firm to firm both for a particular product and for different products, a particular scenario is chosen and shown in each PLET's block diagram demonstrated in Figures 3.2 to 3.5 (on pages 93 to 95).

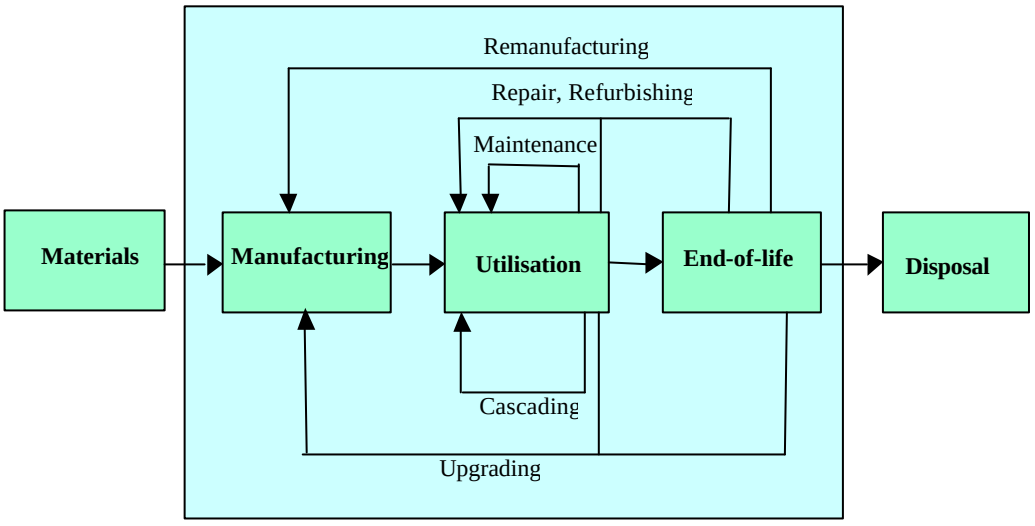


Figure 3.1: Product Life Extension Domain

3.1.1 Repair and maintenance process

This is a product-life-extension process option that is commonly carried out at the usage phase of the product lifecycle. It is concerned with the performance of a wide variety of

activities needed for ensuring the smooth working of equipment and facilities. The totality of repair and maintenance as seen in this work consists of two parts, namely: maintenance, and repair. Maintenance involves the assurance of continual functioning of the machinery to prevent failure by constant observation of some parameters that show the condition of the machinery and correction of any deviation from allowable performance or condition range while repair has to do with the restoration of the machinery to functional condition at the time any fault is noticed[GREE 91, ANDR 97]. The context of the usage of repair and maintenance term in PLETS is limited to inspection, testing, servicing, reconditioning, and rebuilding performed in fixed shop facilities. Refurbishment is categorised as a different option in PLETS. Details of individual operations making up the repair and maintenance process are shown in Figure 3.2a (on page 93).

3.1.2 Refurbishing process

Refurbishing is a process where products are usually brought back to some central facility for processing. In this case, upon disassembly, the parts are kept together such that the original product is reassembled after undergoing necessary operations. In the refurbishing process the serviceable parts are reused within the manufacturer's acceptable wear limits [ANDR 97]. The activities involved in refurbishing process are outlined in Figure 3.2b on page 93. The main difference between repair process and refurbishing process is that only the parts or modules that are needed to be removed to facilitate mending of the faulty parts are dismantled under repair process while complete disassembly of the product is carried out in refurbishing. In addition, the quality of refurbished product is higher than repaired product

3.1.3 Remanufacturing process

It is an after-market/after-use process that revives and restores a used product to like new condition in terms of performance and durability [BANA 95]. It involves bringing reasonably large quantities of similar products into a central facility, disassembling, and sorting the disassembled products into part types which are further treated as the case may require before being reassembled (Figure 3.3 on page 94). Parts from a specific product are not kept together as in refurbishing and repair. Remanufacturing involves a rather high volume factory arrangement similar to new product manufacturing except that the parts flowing to assembly lines are mostly reconditioned parts. In view of the high volume factory arrangement involved, this process is adapted to mass production, which is

characterised by an assembly flow line system like in new product manufacturing. A remanufacturing product has to meet manufacturer's specifications on quality, control and testing like an original product [ANDR 97].

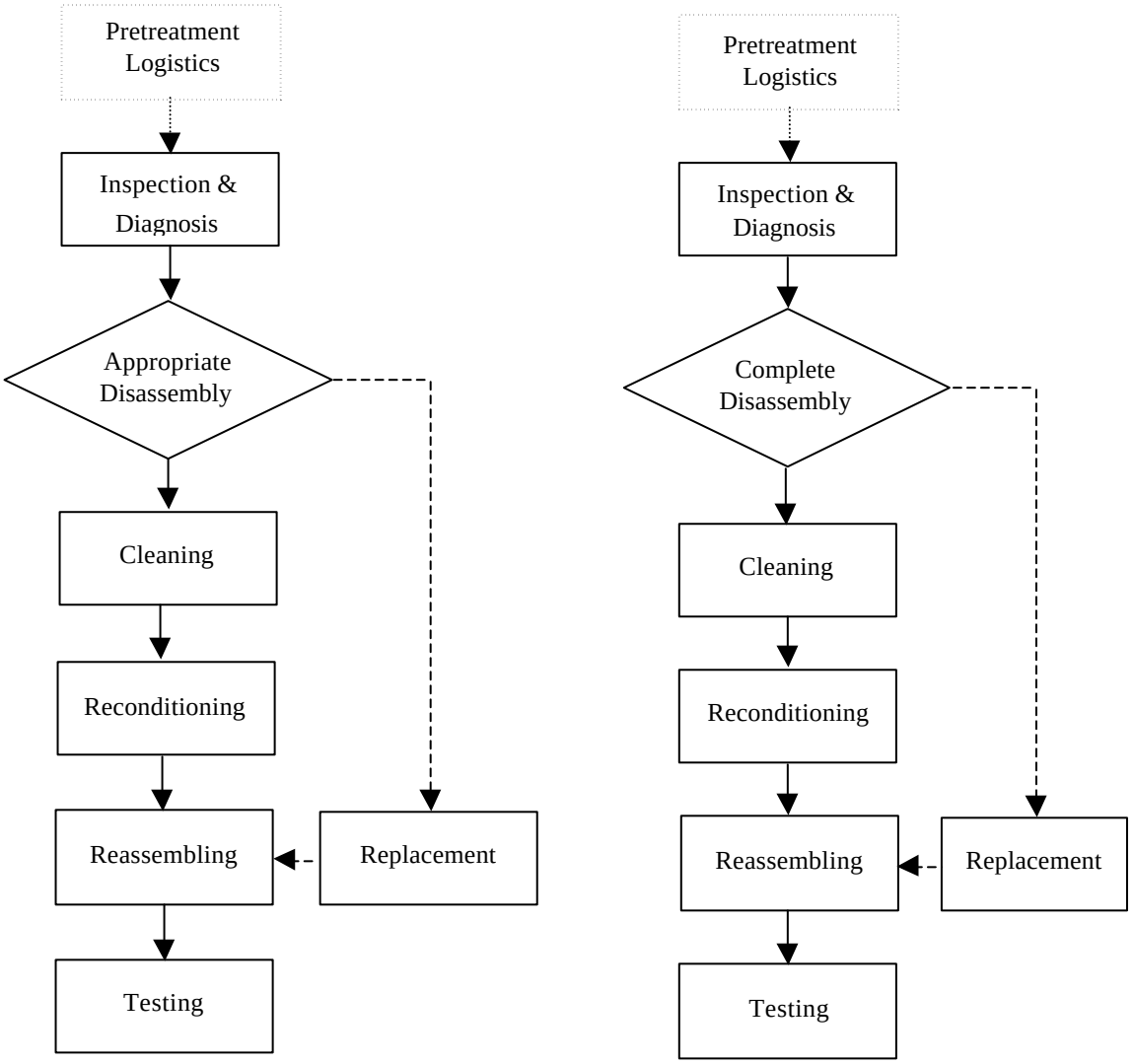


Figure 3.2: The flowcharts of: a) Repair and maintenance process and b) Refurbishing process [ANDR 97]

3.1.4 Upgrading process

This process involves the improvement of product quality to match technological advances by replacing old modular functional components with new. It may also mean adding new module to already existing machine. The process of upgrading may be in the form of mass production as in remanufacturing or in the form of one-to-one process like in refurbishing. Example of an upgrading involving the incorporation of a new module is the

computerisation of a numerical controlled machine to upgrade it to computer numerical controlled machine. Figure 3.4 (on page 95) shows an upgrading process chart.

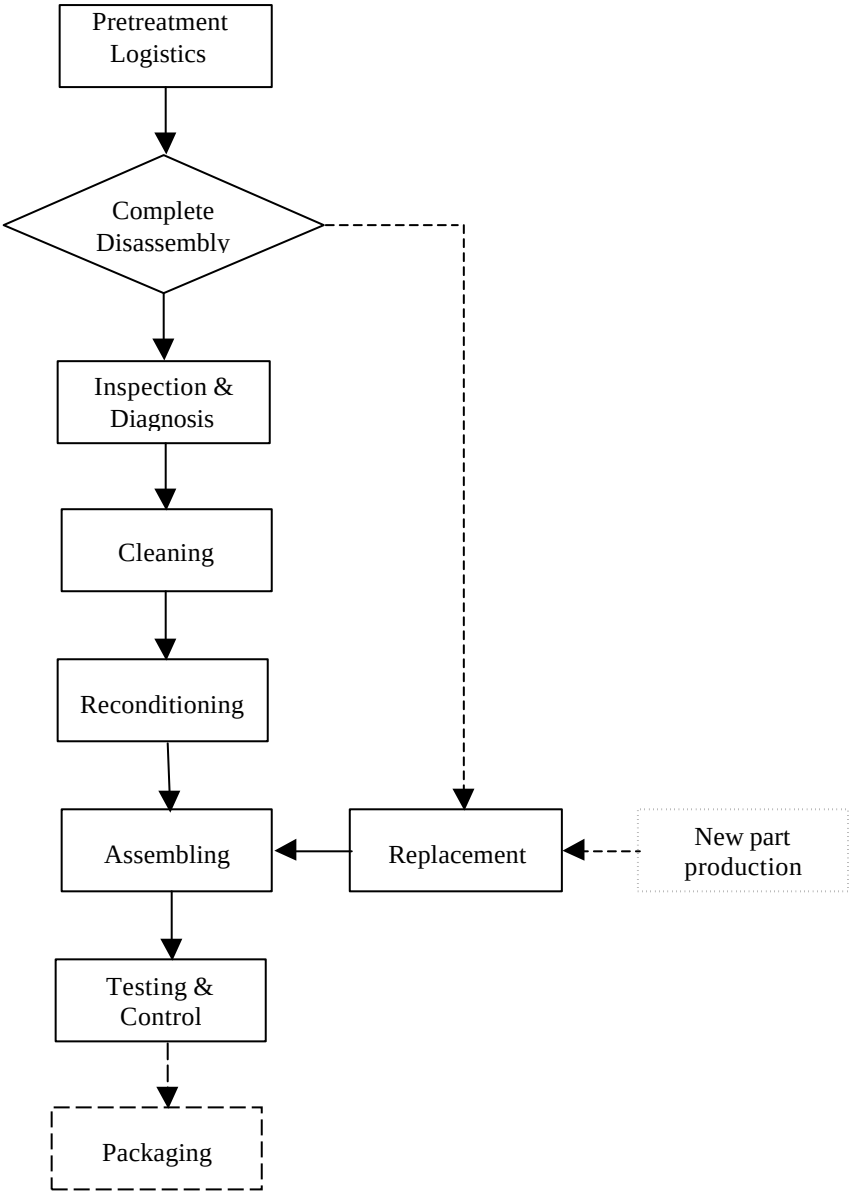


Figure 3.3: Remanufacturing process chart [the idea is obtained from ANDR 97]

3.1.5 Remarketing/Cascading process

Cascading is the process of re-using goods in lower grade uses or the sale of unwanted product to another person/firm. It usually involves exchange of ownership. There are various versions of cascading, such include away-grading, down-grading, and others. This practice is common with investment goods such as trains. The process may be a one-to-one process or mass production process. The process may or may not include reconditioning,

replacement and assembling. Figure 3.5 (on page 96) shows a typical cascading process chart.

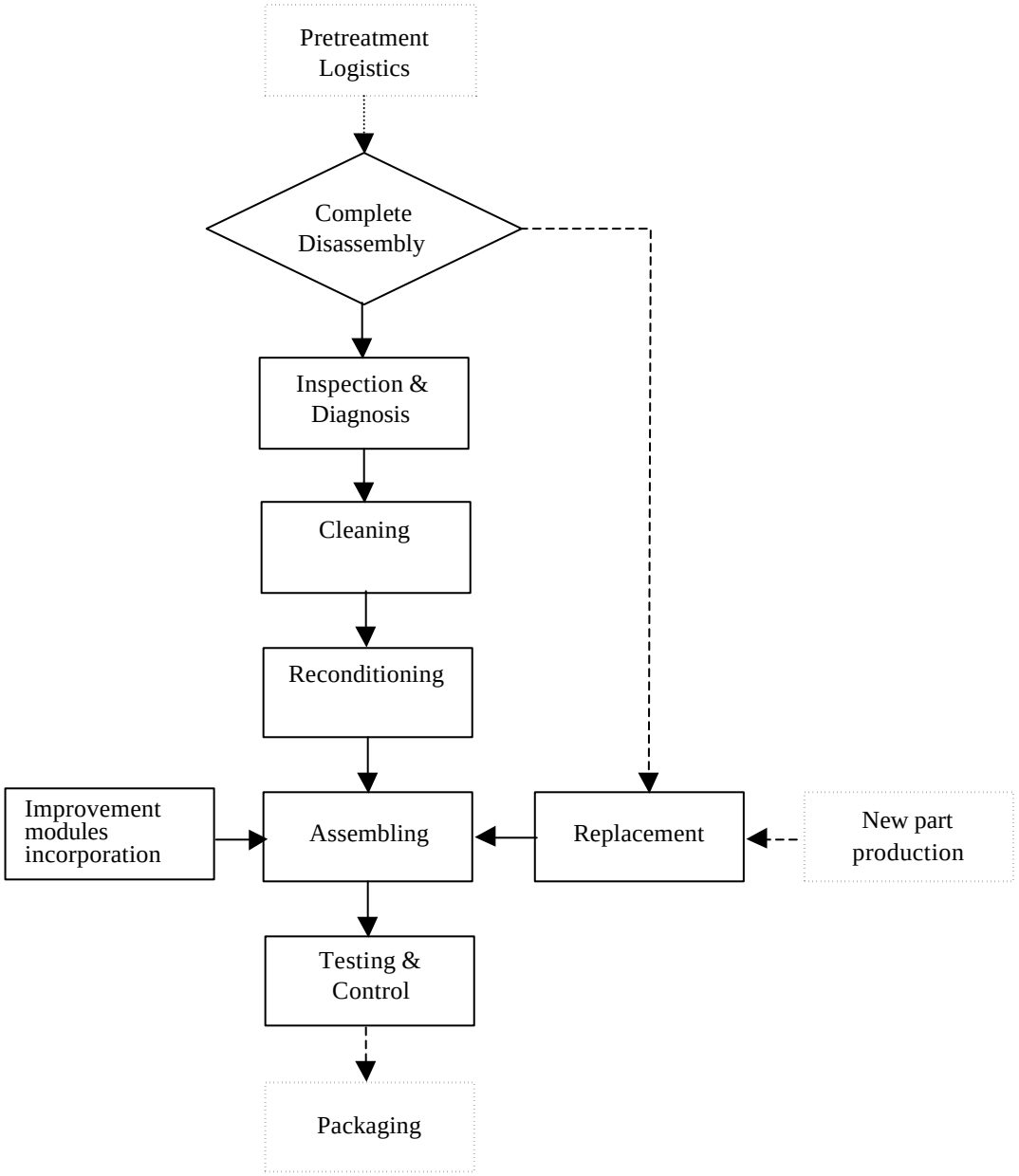


Figure 3.4: Upgrading process chart

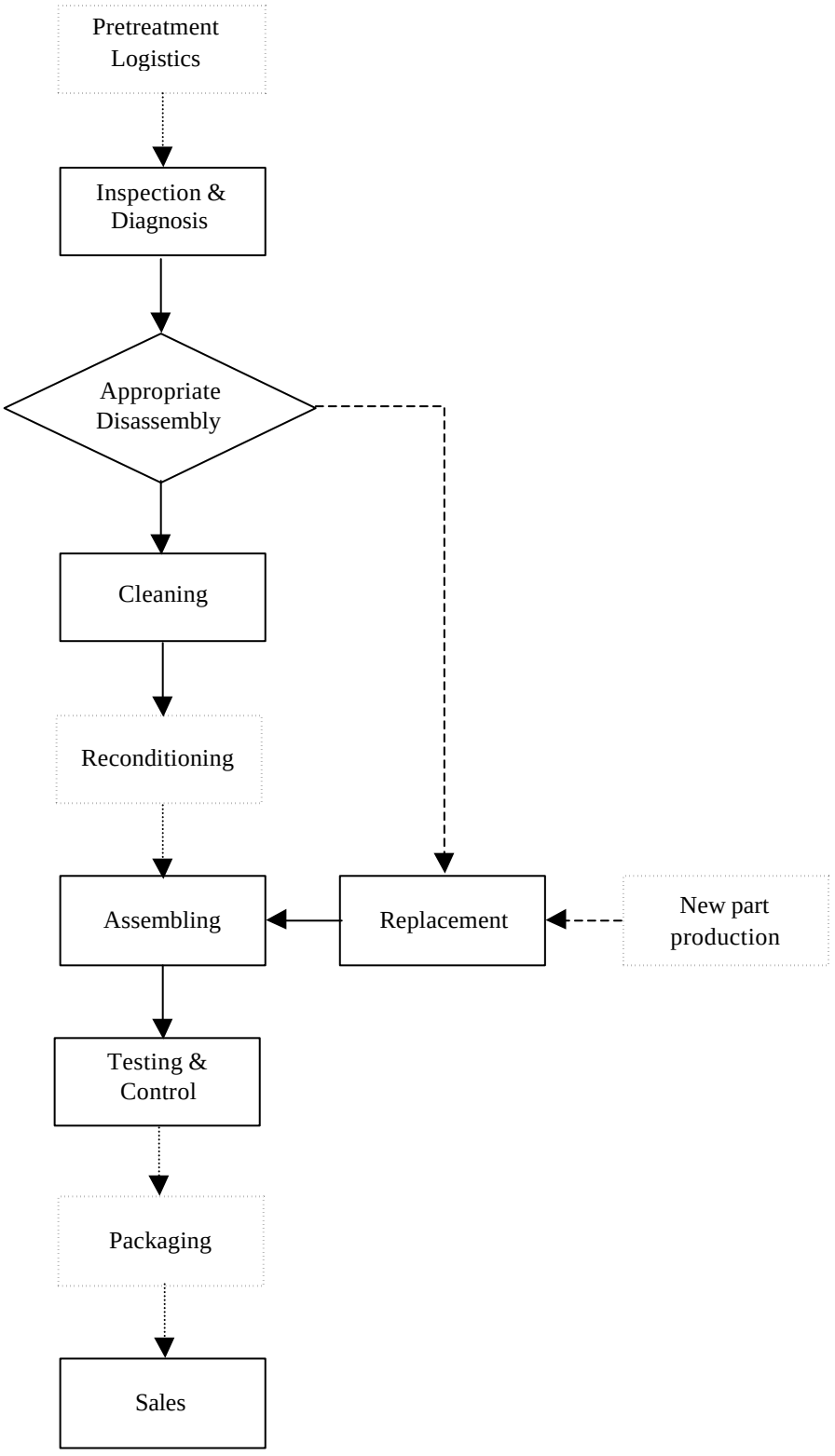


Figure 3.5: Cascading process chart

3.2 Alternative process analysis and evaluation

The study of various decision analysis approaches and applications such as [DEAS 86, NELS 86, CHNA 92, SPBU 94, YUZH 92, DESH 95, LENZ 95] revealed that a utility

function can be used to describe a relationship between a set of attributes of same dimension of value and the degree of utility corresponding to that attribute. After normalisation (see chapter 2), the utility theory can be applied to product life extension process selection. The value or utility of each PLET can thus be calculated as a measure of preference for various values of a variable, having measured the relative strength of desirability that the decision maker has for those values.

Suppose $\{a_1, a_2, ..., a_m\}$ are the feasible PLET alternatives in the decision problem (represented by Figure 3.6) , $\{X_1, X_2, ..., X_N\}$ is a set of attributes, and f_{mn} denotes a specific level of X_n with regard to PLET alternative a_m. Then if axioms of decision theory are to be obeyed and certain preferential and independence conditions hold, then $v(f_{11}, f_{12},..., f_{mn})$ has the form of a simple additive weighted utility value function:

$$v_j(a) = \sum_{i=1}^{N} w_i v_i(f_i) \tag{3.1}$$

where $v_i(f_i)$ = A utility value function over a single attribute x_i

w_i = Preference weight of attribute x_i

$v_j(a)$ = The utility value of PLET alternative a_j on attributes $\{X_1, X_2, ..., X_N\}$

= The summation of the utility value at each of the attributes

These generalised PLET assessment value function (equation 3.1) can be rewritten for each PLET alternative as follows:

Repair and maintenance process value function

$$\begin{aligned} a_1 = {} & w_1[\gamma_1(C_{DRT} + C_{OVH})]_1 + w_2[\gamma_2(T_{PDXT} + T_{PCXT} + T_{TCAP})]_1 \\ & + w_3[\gamma_3(E_{RCSM} + E_{WR} + E_{RCSV})]_1 + w_4[\gamma_4(M_{SUP} + M_{DMD})]_1 \\ & + w_5[\gamma_5(t_{SUT} + t_{AUXT} + t_{APOT} + t_{DET})]_1 + w_6[\gamma_6(L_{NIS} + L_{PIS})]_1 \end{aligned} \tag{3.3}$$

Refurbishing process value function

$$\begin{aligned} a_2 = {} & w_1[\gamma_1(C_{DRT} + C_{OVH})]_2 + w_2[\gamma_2(T_{PDXT} + T_{PCXT} + T_{TCAP})]_2 \\ & + w_3[\gamma_3(E_{RCSM} + E_{WR} + E_{RCSV})]_2 + w_4[\gamma_4(M_{SUP} + M_{DMD})]_2 \\ & + w_5[\gamma_5(t_{SUT} + t_{AUXT} + t_{APOT} + t_{DET})]_2 + w_6[\gamma_6(L_{NIS} + L_{PIS})]_2 \end{aligned} \tag{3.4}$$

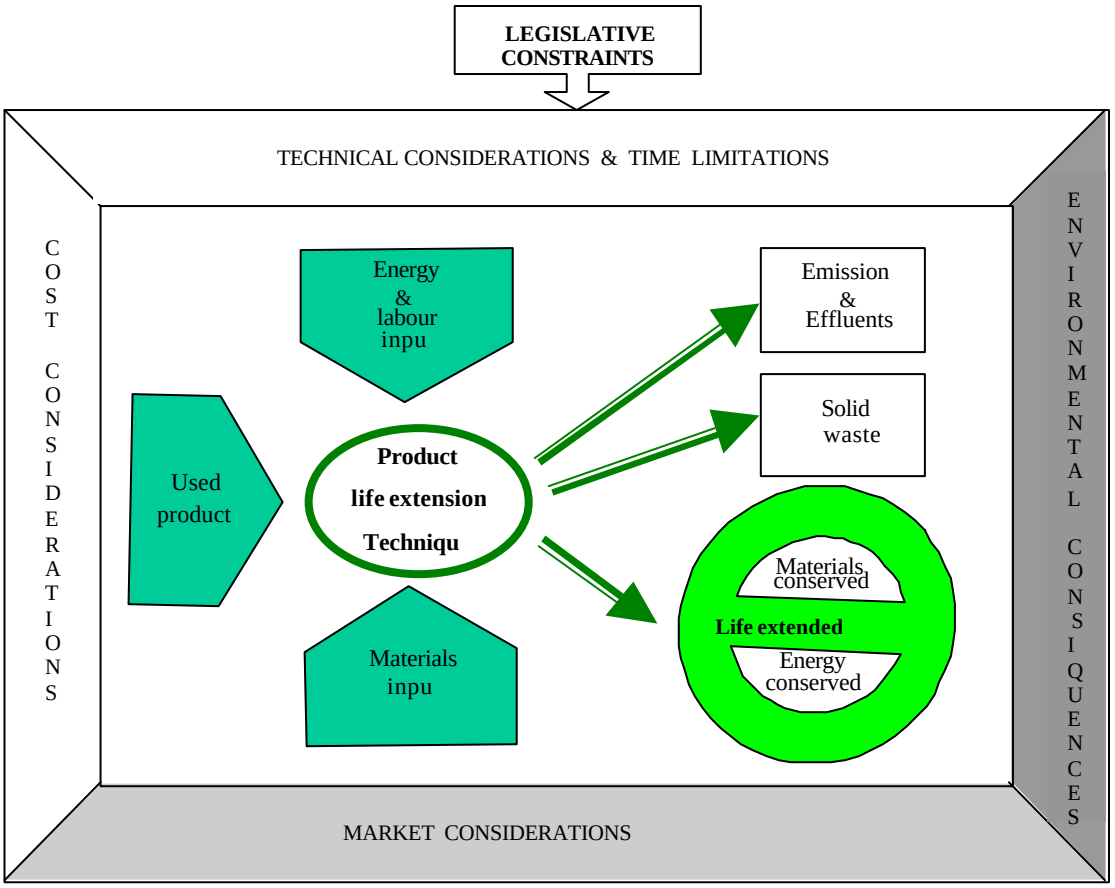


Figure 3.6: Product life extension decision making context

Remanufacturing process value function

$$a_3 = w_1[\gamma_1(C_{DRT} + C_{OVH})]_3 + w_2[\gamma_2(T_{PDXT} + T_{PCXT} + T_{TCAP})]_3 + w_3[\gamma_3(E_{RCSM} + E_{WR} + E_{RCSV})]_3 + w_4[\gamma_4(M_{SUP} + M_{DMD})]_3 + w_5[\gamma_5(t_{SUT} + t_{AUXT} + t_{APOT} + t_{DET})]_3 + w_6[\gamma_6(L_{NIS} + L_{PIS})]_3 \quad (3.5)$$

Upgrading process value function

$$a_4 = w_1[\gamma_1(C_{DRT} + C_{OVH})]_4 + w_2[\gamma_2(T_{PDXT} + T_{PCXT} + T_{TCAP})]_4 + w_3[\gamma_3(E_{RCSM} + E_{WR} + E_{RCSV})]_4 + w_4[\gamma_4(M_{SUP} + M_{DMD})]_4 + w_5[\gamma_5(t_{SUT} + t_{AUXT} + t_{APOT} + t_{DET})]_4 + w_6[\gamma_6(L_{NIS} + L_{PIS})]_4 \quad (3.6)$$

Cascading/ Remarketing process value function

$$a_5 = w_1[\gamma_1(C_{DRT} + C_{OVH})]_5 + w_2[\gamma_2(T_{PDXT} + T_{PCXT} + T_{TCAP})]_5 + w_3[\gamma_3(E_{RCSM} + E_{WR} + E_{RCSV})]_5 + w_4[\gamma_4(M_{SUP} + M_{DMD})]_5 + w_5[\gamma_5(t_{SUT} + t_{AUXT} + t_{APOT} + t_{DET})]_5 + w_6[\gamma_6(L_{NIS} + L_{PIS})]_5 \quad (3.7)$$

where C_{DRT} ---- Direct costs

C_{OVH} ---- Overhead cost

T_{PDCD} ---- Product condition

T_{PCXT} ---- Process characteristics

T_{TCAP} ---- Techno-capability

E_{RCSM} ---- Resource consumption

E_{WR} ---- Waste released

E_{RTMC} --- Waste release impact

E_{RCSV} ---- Resources conserved

M_{SUP} ---- Supply score of resources required by the PLET to reprocessed the product

M_{DMD} ---- Demand score of the PLET reprocessed product

t_{PLET} ---- Estimated required time to carry out the PLET option

t_{SUT} ---- Set-up time

t_{APOT} ---- Actual process operations time

t_{AUXT} ---- Auxiliary times

t_{DET} ---- Delay time

L_{NIS} ---- Negative legislative score of the PLET

L_{PIS} ---- Positive legislative score of the PLET

g_1 ---- Normalising function for cost attribute f_1

g_2 ---- Normalising function for technical attribute f_2

g_3 ---- Normalising function for environmental attribute f_3

g_4 ---- Normalising function for market attribute f_4

g_5 ---- Normalising function for time attribute f_5

g_6 ---- Normalising function for legislative attribute f_6

3.3 Sensitivity Analysis

Sensitivity analysis, which refers to the study of how important results changes with changes in estimates, is a “what-if” technique that looks at how a result will be changed if assumptions change or original estimates are not achieved. It is applicable in any analytical technique involving uncertainty in their underlying assumptions [ANCL 91, SALV 92]. It is recognised as an aid for validating the model and for identifying model improvement possibilities[SPBU 94]. Sensitivity analysis may be carried out numerically or by differentiation. Numerical sensitivity analysis can either be displayed as absolute amounts

or as percentage changes from the base estimates or both. In this work, the percentage – change-based analysis is applied by changing the estimates in increments of plus and minus ten percent and recomputing the results. Consequent on the uncertainty in the accuracy of eco-industrial data collected and lack of enough data for evaluation, sensitivity analysis of how variation in data affect the PLET performance and the effect of preference changes on the decision outcome will be analysed at attribute and multi-attribute levels respectively.

3.4 PLET Alternative Selection Decisions

After assessing each PLET alternative on the six attributes, the results have to be compared with the satisfaction of minimum standard on each of the attributes. The final selection of the PLET alternative to be used for the extension of a particular product in a specific location can be based on three principles, namely: satisficing solution, maximisation of expected utility, and preferred solution [YUZH 92, SPBU 94].

3.4.1 Satisficing solution (a_{sa})

The set of satisficing solutions consist of all processes that meet minimal requirements:

$$a_{sa} = \left\{ a_i \left| \sum_{i=1}^{I} w_i v_i(f_i) \geq \left[\sum_{i=1}^{I} w_i v_i(f_i) \right]_{\min} \right. \right\} \tag{3.8}$$

where $\left\{ \sum_{i=1}^{I} w_i v_i(f_i) \right\}_{\min}$ = Minimum total acceptable performance

Further details on set minimum standard on each PLET attribute can be found in chapter 2 section 2.2.

3.4.2 Maximum benefit solution (a_{mb})

This decision is for a decision-maker in favour of maximising expected utility/benefit. In this case, recourse is not made to minimum satisfactory condition level with respect to any attribute. Thus this solution is purely based on compensatory method that permits trade-offs between the attributes. This decision maker will select the PLET:

$$a_{mb} = \left\{ a_i \left| \max \sum_{j=1}^{N_j} w_j v_{ij}(f_i) \middle/ \sum_{j=1}^{N_j} w_j \right. \right\} \tag{3.9}$$

3.4.3 Preferred solution (a_{pr})

This solution is both satisficing and benefit maximising. This solution is the one utilising the integration of both compensatory and non-compensatory techniques, combining the advantages of the methods. This means, select the PLET a_{pr} such that:

$$a_{pr} = \left\{ a_i \left| \max \sum_{j=1}^{N_j} w_j v_{ij}(f_i) \middle/ \sum_{j=1}^{N_j} w_j \right. \right\} \geq \left[\sum_{j=1}^{N_j} w_j v_{ij}(f_i) \middle/ \sum_{j=1}^{N_j} w_j \right]_{\min} \tag{3.10}$$

Depending on the nature of the decision maker, represented by the three upmentioned decision making principles, substituting all the relevant values obtained from equations 3.3 - 3.7 and equations 2.65 -2.71 into any of equations 3.8 - 3.10 results in an optimal product life extension process selection.

3.5 Computer Implementation of PLET Selection Model

The comprehensiveness of this model and the data requirements with the attendant calculations and analyses make the application of the methodology tedious without the use of computer. Computer application does not only quicken the implementation of the model but also facilitates easy and fine presentation of the implementation results. This model can be easily implemented on a computer by using any of the windows application programmes such as Visual basic, Visual C++ and others. However, MS Excel is used in this work to develop the demonstrative computer implementation prototype. The prototype can later be upgraded to a decision support tool for selecting industrial processes with regard to product life extension. This demonstrative computer prototype also supports the decision model in assessing other parameters like the life-extendibility of the retired product, marketability of the reprocessed product and the cost of adopting a specific process in extending the life of the retired product. Furthermore, it facilitates the evaluation of available facility's suitability for the process and consequently for the chosen reprocessed product quality. The process time, and the conformity of the process to legislative requirement can equally be determined by using the computer application prototype.

3.5.1 The computer implementation prototype's structure and workings

The prototype is a demonstrative DSS. It is divided into three sections, namely: the INFOCOL, the INFOPRO and the INFORES. The INFOCOL, which means information collection module, is the information/data collection part involving the interaction between the computer, the methodology and the decision-maker. It is the stage at which the decision-maker defines his goal by answering a number of questions posted on the computer. These questions are divided into six groups/sheets according to the groupings of the decision criteria, namely: Codacol, Tedacol, Endacol, Madacol, Tidacol and Ledacol. These answers serve as input data for the INFOPRO. INFOPRO refers to information processing module. It basically consists of a collection of mathematical models representing simple computational and analytical expressions that correlates complex relationships among many variables that evaluates a PLET. The data collected at each of the INFOCOL sheets are linked with the corresponding sheet in the INFOPRO i.e. the cost data entered at Codacol sheet of INFOCOL is linked with Costpro sheet of the INFOPRO where all cost calculations are carried out. The same linkage is followed from Tedacol to Techpro, Endacol to Envpro; Madacol to Mktpro; Tidacol to Timpro and Ledacol to Legpro. The results of the calculations made in these sheets are then passed to the INFORES. INFORES refers to information result-displaying module. It prioritise the PLET alternatives on the basis of the result of the analysis made at the INFOPRO. These results are displayed in linguistic-, tabular-, and graphical forms. The results are first presented attribute by attribute and finally in combined form. The computer prototype ends-up with recommending the "best" PLET for each attribute and for the multicriteria consideration. This enables a decision-maker with different interest to know and choose the best PLET under such condition. Figure 3.7 shows the illustration of the modularisation of the computer prototype into phases and sheets, while Table 3.1 shows sample display of INFORES. When none of the PLET alternatives satisfy all the set minimum standards, the decision maker have the choice of either reviewing one or more of the set minimum standards or seek for non-product life extension alternatives. Further details on the constituents of PLETS' INFOCOL will be found in the appendix.

3.5.2 Limitations of the computer prototype

The only know limitations of this implementation prototype is that it only permits entering data for maximum of 10 types of individual resources and there are even some points where provisions are made for only 5 types.

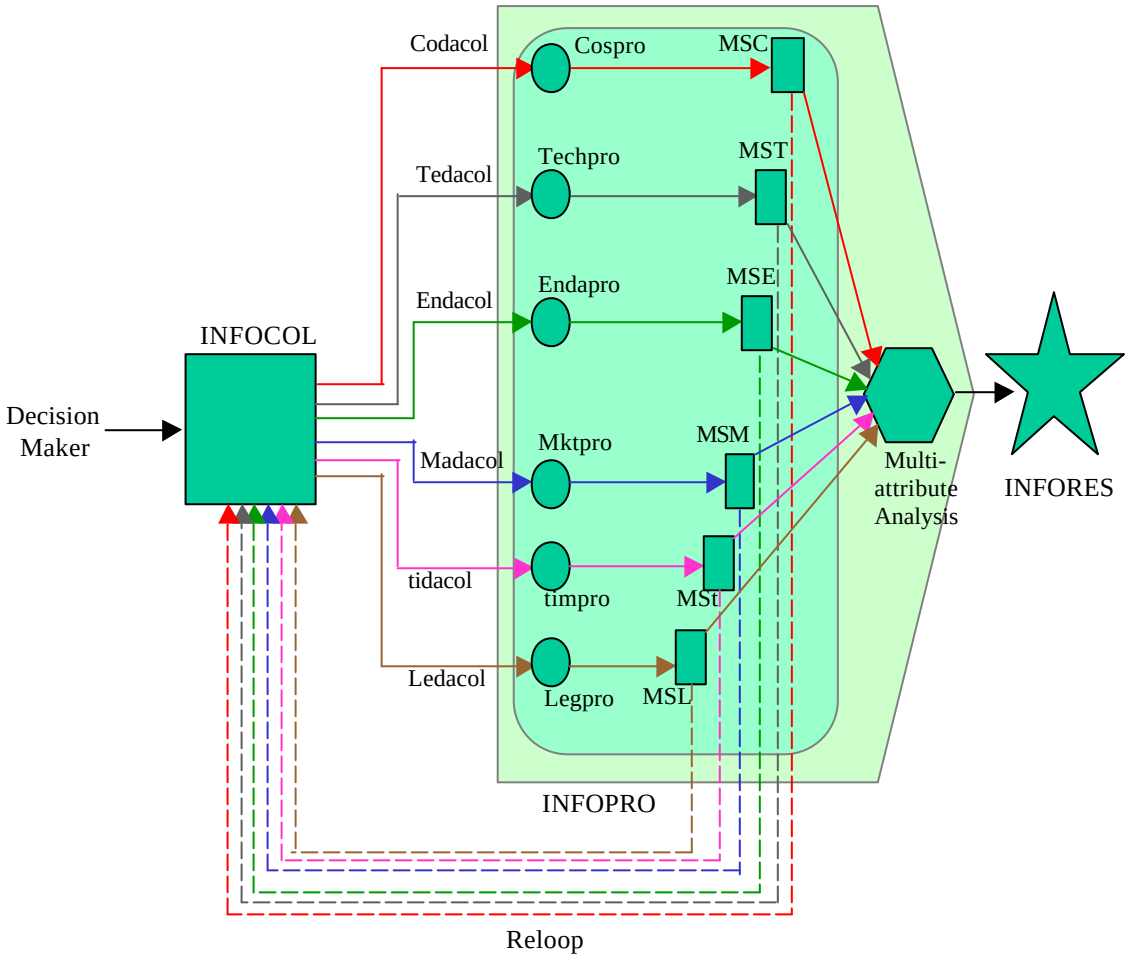


Figure 3.7: The structure of PLET selection model's computer implimentation prototype

[Codacol	Cost data collection	Cospro	Cost data processing
MSC	Minimum standard on cost	Tedacol	Technical data collection
Techpro	Technical data processing	MST	Minimum standard on technology
Endacol	Environmntal data collection	Envpro	Environmental data processing
MSE	Minimum standard on Environment	Madacol	Market data collection
Mktpro	Market data processing	MSM	Minimum standard on Market
tidacol	time data collection	timpro	time data processing
MSt	Minimum standard on time	Ledacol	Legislative data collection
Legpro	Legislative data processing	MSL	Minimum standard on Legislation]

The recommended product life extension process on the basis of:			
Cost	**attribute is**	**Refurbishing**	**process**
Technical		**Cascading**	
Environmental		**Cascading**	
Market		**Upgrading**	
Time		**Cascading**	
Legislative		**Remanufacturing**	
The recommended product life extension process after considering the satisfaction of set minimum standard on each attribute:			
Cost	**attribute is**	**Refurbishing**	**process**
Technical		**Cascading**	
Environmental		**Cascading**	
Market		**Upgrading**	
Time		**Cascading**	
Legislative		**Remanufacturing**	
The priority listing of product life extension processes on the basis of :			
Unweighted multiattribute consideration		Weighted multiattribute consideration and meeting overall minimum standard	
1. Repair 2. Refurbishing 3. Cascading 4. Remanufacturing 5. Upgrading		1. Repair 2. Refurbishing 3. Cascading 4. Remanufacturing 5. Upgrading	
The preferred PLET is: Repair process			

Table 3.1: A sample of INFORES display of results

The case study, which tests and illustrates the application of this model and its companion computer implementation prototype, will be found in the next chapter.

4 Model Testing with a Case Study

4.1 Model testing methods

According to [MTMA 92], the validity and the reliability of a model can be defined and evaluated in terms of its relationship to the intended use. One of the methods of determining the validity of a model is by testing the overall performance of the model and the prescriptive power of the model in comparison with management intuition i.e. by introducing a variety of real data in order to see whether the model predictions make sense. Another method is by finding out from the opinion of the decision maker if the model behave like the real system. This can be achieved by presenting a knowledgeable decision maker with two or more sets of data and asking him to decide which one came from a model and which one came from a real system. If he cannot tell the difference, the model passes the test. These two methods could have been used, but the attempts made in respect of the second method were unfruitful. The responses of the decision-makers were very poor. To ascertain the validity of this model, it was run with a set of data on a multipurpose shelling machine and the obtained results are compared with the expected result.

In addition to validating the methodology, the case study also illustrates the use of the computer prototype. The choice of the multipurpose shelling machine as a case study is based on its being a typical agro-processing machine of importance to agrarian economy. The choice of the machine as case study was also based on the in-depth knowledge of this machine by the author and because of the availability of some data needed in demonstrating the use of the proposed methodology.

4.2 The shelling machine

4.2.1 Features of the shelling machine

The 5hp electric motor driven 450kg/hr throughput capacity sheller (shown in Figure 4.1) was developed at FIIRO by the author. It consists of four sections, namely: the feeding unit, the decorticating unit, the separation/cleaning unit and the discharging unit. The feeding section consists of a hopper and a feed regulation device. The 5kg peanut holding capacity trapezoidal shaped hopper facilitates free flow of undecorticated crop produce into the shelling chamber. It was constructed from galvanised steel. The simple feed regulator consists of two long U-shaped plates (serving as shutter guide) welded to the opposite sides of the upper half of the shelling chamber just below the lower end of the

hopper, and a 44cm by 12cm L-shaped shutter with a handle. The regulator distributes and delivers the crop material to the decorticating unit in a steady, uniform flow. The feeding rate is controlled by manually adjusting the shutter opening.

The decorticating unit is the main functional unit of this machine. It is made-up of a cylinder, a concave and an adjuster. The 44cm long, 30cm diameter cylinder consists of eight shelling bars, two thick cylinder plates with 30mm steel bushings and eight pairs of circumferentially drilled holes for mounting bars, and a driving subassembly. The semi-circular concave constructed from a 2mm thick galvanised steel is slotted parallel to the cylinder's direction of motion. The adjuster consists of four independently adjustable concave mountings and fasteners which facilitates the variation of the cylinder-concave-clearance. The operation of this unit is accomplished with the working of a rotating cylinder against a curved, grated section called concave. Material flow past the cylinder perpendicular to the axis of cylinder's rotation.

The separating/cleaning unit consists of a fan with two shutters for regulating air inflow, and a chute with 30° inclination to the horizon. The cleaning mechanism is based on aerodynamic principle that separates two components in terms of differences in their suspension velocities[1]. Air is blown across decorticated nuts that are falling under gravity, thereby separating the shell from the kernels. The delivery unit is integrated with the cleaning unit. It has two openings. The frontal opening serves as exit for the shells while the lower opening serves as an exit for the kernels.

4.2.2 The unique characteristics of the FIIRO developed multipurpose sheller

- **Easy disassembly and convertibility**

The ease with which the machine can be dismantled is far better than all imported and other locally developed ones. The important parts such as the decorticating chamber which are easily affected by tear, wear and clogging during use were made easily accessible and disassemblable. The cylinders of all previously developed shellers seen cannot be dismantled to the level which this one can be. This characteristic makes it easy to change the shelling bars and the cylinder, thereby affording the user to convert the machine for multipurpose use. The shelling bar features, concave type, and cylinder-concave clearance determines the grains that could be shelled by the machine. For instance, knife-like tooth is

[1] The suspension velocity is the air velocity required to support the pieces of materials against the action of gravity in a vertical air stream. *Principles of farm machinery p. 418*

required to thresh locust bean while nut-like tooth is required to shell maize. Furthermore, finger-like tooth is required to thresh guinea corn and rice, and to shell cowpeas and soybeans. Consequently, by simply replacing a particular type of bars on the spike tooth cylinder with another, the machine is ready to thresh or shell another type of grain. Similarly by replacing the spike tooth cylinder with rasp bar cylinder, the machine can shell groundnut. It can also dehull rice by replacing the cylinder with worm-like block cylinder. The concave type, cylinder- and fan speeds also have to be changed. The cylinder-concave clearance also has to be adjusted to suit the crop decortication.

Figure 4.1: FIIRO developed multipurpose sheller [DUNM 92]

- **Cost**

The cost of producing the machine with such capacity is relatively cheap in comparison with imported ones. This has been due to the fact that all the parts and materials used except the electric motor are locally produced. It was also the in-house technical skill that was used. The lifecycle cost of the machine is also expected to be low because the service cost will be small. Easy accessibility makes the disassembly time to be low and consequently the labour cost will be low. Unlike other shellers in which when a small part is damaged that a whole sub-assembly have to be replaced, the majority of the parts of this sheller are joined by easily dissolvable connectors. Only the damaged parts need being replaced and thereby reduced parts and material cost.

- **Environmental friendliness**

The compositions of the materials used for the fabrication of the machine are environmentally safe. Their choice was based on cost, durability and toxicity. Galvanised steel and tool steel are the two main materials used in the development of the machine. None of them are toxic. They are also wear resistant. This is an essential feature for food processing application, because metal particles in the output can negatively affect the quality of product processed by the machine.

4.3 Sheller evaluation parameters

Apart from the upmentioned factors, qualities of shelling machines are commonly evaluated in terms of throughput capacity, shelling efficiency, percentage breakage, and cleaning efficiency [DUMA 90]. Table 4.2 shows the performance characteristics of some previously developed shellers and the estimated performance of the new machine on groundnut. Other parameters that can be used to assess how good a sheller is, include: variability of the cylinder speed, 'changability' of the cylinder bar type, variability of cylinder-concave clearance, and 'changability' of the concave type.

- **Throughput capacity**

This is the quantity of peanuts that a sheller can process per hour. The suitability of a specific shelling machine in terms of throughput capacity depends on the scale of operation intended by the user. With 450 kg/hr throughput capacity of this shelling machine, it can process about 3.5 tonnes of peanuts per 8hours workday. This makes it suitable for medium size industrial application.

- **Shelling efficiency**[2]

This refers to the fraction of the total quantity of peanut input that is decorticated by the machine. It depends on the configurations and operations of the decorticating unit. It is expressed in percentage. Thus the higher the value the better. Test evaluation of a similar sheller was reported to be 92.2% [DUMA 90].

[2] Shelling efficiency =[total pods input-(unshelled pods + unshelled capsules)]/total pods input

- **Percentage breakage**[3]

This factor assesses the quantity of broken kernels out of the total quantity of nuts shelled. This should be as low as possible. This factor also depends mainly on the configuration of the decorticating unit. A similar sheller evaluated for this parameter was reported to have 2.2% breakage of kernels [DUMA 90].

- **Cleaning efficiency**[4]

This expresses how well the machine separates the husks from the seeds. Cleaning efficiency depends on a number of factors such as moisture content of the pods and the fan speed. The cleaning efficiency of a similar sheller was found to be 90.9% at 2050 rpm of the blower impellers [DUMA 90].

Sheller model	**Performance indices**				
	Through-put capacity (kg/ hr)	Shelling capacity (kg/hr)	Shelling efficiency (%)	Percentage breakage (%)	Cleaning efficiency (%)
Kharagpur[5]	150	-	98.5	9	-
TNAU	400	260	95	4.5	98
AIT 84	-	210.5	98	2.3	-
AIT 90	400	280	98.05	4.53	-
FIIRO 92	450	295	98	4.45	96

Table 4.1: Comparison of Performance characteristics of a number sheller models [DUNM 92, GOGS 90, SISB 78]

4.4 The Feasible PLET Alternatives

The main determinants in the choice of the best process for the extension of the lifecycle of threshers and shellers are the type of decision maker, the product condition, and others. The decision maker category being considered is the manufacturer under product take back obligations, and the PLET alternatives considered feasible for this test case are:

Alternative 1: Restore the product to functional condition (Repair and maintenance)

In this case, the machine is diagnosed to determine the parts whose configuration has changed from the appropriate specifications, these parts are then dismantled and readjusted

[3] Percentage breakage = broken kernels/(broken kernels + whole kernels) x100%

[4] Cleaning efficiency = Husk in the blower outlet/(husk in the blower outlet and kernel outlet).

[5] Kharagpur model was developed at Rice Process Engineering Centre, I.I.T., Kharapur, India; TNAU model was developed at Tamilnadu Agri. Univ., Coimbatore, India; AIT 84 model was developed in 1984 at Asian Institute of Technology, Bangkok, Thailand; AIT 90 model was a modified version of AIT 84 model; FIIRO 92 model was developed in 1992 by the author at the Federal Institute of Industrial Research, Oshodi , Nigeria.

or replaced with new parts if the parts cannot be reconditioned. The readjustment of parts may be time-based or condition-based depending on the manufacturer specifications and /or agreement with the manufacturer. The main unit usually requiring rework in a spike toothed Sheller is the decorticating unit in which the spike tooth of the cylinder may be bent or broken. Other parts that commonly require adjustment and replacements are the fasteners and members that are under repeated vibrations and fatigue. The fasteners holding down the cylinder bars may also become loosened. The rotary parts are also oiled or greased as the case may require.

Alternative 2: Restore the product to a specified functional quality (Refurbishing)

The specified functional quality of "overhauling" often require completely taking the product components apart, inspection, cleaning, reconditioning[6], reassembling, as well as re-calibration and tests of modules and the whole product. It involves a more thorough job than in repair and maintenance. In this test case, every unit of the sheller is dismantled, checked, cleaned and necessary components reworked or replaced. All activities/operations are carried out on a sheller before any action begins on the next one.

Alternative 3: Restore the product to "as new" condition (Remanufacture)

This option entails making the functional performance of the old product just as a new one. In this process, the old product is completely dismantled and sorted into parts. Individual component of the product is inspected and treated by cleaning/reconditioning to ensure their conformity to "as new" condition both in function and in geometric configuration. The unserviceable parts are replaced with new parts before reassembly. Calibration and tests then follow the reassembly. The process is completed with packaging. A sheller can basically be made to become "as new" in its functional performance quality by carrying out the following: a) making sure that the distributor/shutter of the feeding unit is 'fault-free'; b) changing the faulty spike tooth sub-units, and ensuring that the concave is clog-free; c) ascertaining the effectiveness of the cylinder-concave clearance adjuster(s), and d) ensuring perfect condition of the fan blades and the air track.

[6] Reconditioning is here used to include such activities like greasing, lubricating, bolt tightening, twisting, any any other similar readjustment actions carried out.

Alternative 4: Improve the quality of the product (Upgrading)

The performance quality of the sheller can be improved in a number of ways, namely: by either a) modifying the functional unit(s) that will facilitate easy use of the machine for shelling different types of grain (multipurpose use); b) incorporating some modules into the machine to improve shelling efficiency; c) modifying some parts to reduce percentage breakage; d) introducing units that will improve separation/cleaning efficiency of the machine; e) simplifying the feeding regulators and/or clearance adjuster(s); and f) improving the throughput capacity of the machine by increasing the dimensional configuration and the power of the driving motor. This process is essentially the same as remanufacturing but for the replacement of obsolete modules and the incorporation of new modules at some stage in the process.

Alternative 5: Dispose the product for lower degree of usage (Cascading)

This mainly consists of dismantling the machine into parts and subassemblies for the purpose of economically disposing off the used product. The process basically consists of dismantling the retired product either into functional units or into individual components, cleaning them, sorting them, and sell. In this case, the motor, the belts, pulleys, cylinder, concave, fan and fasteners are components that can be offered for sale.

4.5 PLETs' evaluation on attributes

Questionnaires were formulated and sent to twenty-seven companies out of which only two responded positively. The questionnaires were taken to second hand machine fair at Leipzig to collect information, again only one company responded on the spot while others that promised to reply did not. Eventually data collected from the shelling machine designed and developed by the author at FIIRO were used. Other data were collated from the books and journals. Other relevant data were incorporated based on experience. Details of these data will be found in the appendix.

4.5.1 PLETs' evaluation on cost attribute

The cost calculation is based on monthly period. The estimated quantity of product expected to be taken back per month is 250 units of the shelling machine. Because this is a product life extension service, it forms the basic material input introduced into the process at the beginning of each process. It is assumed that the average unit cost of taking back a

sheller in the period under consideration is 180DM. The other stage of introducing material to the process is at replacement operation stage. The parts that commonly require reconditioning are concave, and fasteners. In this case, the process cost is taken to be the cost of reworking the product. The sales costs are excluded because sales operation is not regarded as an integral part of a PLET in this case. Having collected cost data of various categories, the major costs of each PLET are calculated by substituting relevant cost data into equation 2.4 and its appendages. Using the cost information in the appendices A and B, the 'unweighted' repair process cost per unit reworked product:

$$
\begin{aligned}
v_1(f_1) &= (C_{PLET})_{11} \\
&= C_{RWG} \\
&= C_{FTR} + C_{AO} \\
&= (C_{DRT} + C_{FO} + C_{AO} \\
&= C_{DM} + C_{DL} + C_{FO} + C_{AO} \\
&= 180.00 + 11.13 + 26.70 + 9.56 \\
&= 227.39 \text{ DM}
\end{aligned}
$$

The cost of other process alternatives can similarly be computed to obtain the values shown in Table 5.1 in chapter 5. The individual operations cost of each PLET is also compared with the minimum standard on cost. For details on minimum standard on PLETs' costs see section 4.6.1.

4.5.2 PLETs' evaluation on technical attribute

The technical attribute value calculations are based on mathematical expressions and Tables provided by this work. The analysis of the technical attribute of this shelling machine life extension is as follows:

- **Product characteristics**

A machine's degree of complexity is assessed in terms of the number and variety of different types of: materials used, the geometric configuration of components making up the whole assembly, and the liaisons used in joining the components together. The higher these go the more difficult it is to rework the product. The FIRRO developed sheller is regarded as being generally simple because it is constructed from two materials, namely:

galvanised steel and mild steel. The joints are also secured by two methods, namely: bolts and nuts, and welding. Furthermore, the components and consequently the whole assembly are made of simple shapes. With full consideration of these three upmentioned factors, comparative evaluation of the PLET alternatives in terms of the shelling machine complexity is carried out by using complexity part of equation 2.49 and Table 2.13. Therefore, the repair process complexity score:

$$T_{CXS} \in [0, 1] \quad \text{(choose from Table 2.2.1)}$$
$$= 0.9$$

The normalised result of this evaluation can be found in chapter 5. With regard to product condition, only minor rusts and wears are found in the shelling machine because the materials used are not easily corroded. The thickness of the materials used as well as the smallness of the fatigue to which the sheller is being subjected during operations also makes the shear minimal. Using product condition part of equation 2.49 and Table 2.14, the sheller condition's degree of suitability for the repair process is evaluated in comparison with other PLETs to obtain the normalised assessment values in Table 5.3. Thus, the repair process raw score in relation to product condition is:

$$T_{PDCD} \in [0, 1] \quad \text{(choose from Table 2.14)}$$
$$= 0.9$$

The repair process raw score with regard to the shelling machine characteristics from equation 2.13 is given by the expression:

$$T_{PDXT} = T_{CXS} + T_{PDCD}$$
$$= 0.9 + 0.9$$
$$= 1.8$$

This value is then normalised.The normalised product characteristics scores will be found in chapter 5.

- **Process characteristics**

The effectiveness and impact of all methods employed for each PLET operation on the shelling machine is evaluated under process operations module of this sub-attribute, while

the number of operations and the extent of individual operation needed to meet the reworked shelling machine quality requirement are evaluated under thoroughness factor. Thoroughness score are evaluated by using equation 2.50 and Table 2.16. In this decision context, the comparative thoroughness ratings of each of the eight operations making up the repair process are: pre-treatment logistics (0.3), diagnosis (0.7), disassembly (0.7), cleaning (0.7), reconditioning (0.7), reassembly (0.7) and testing (0.7) operations. The comparative thoroughness requirement rating of the PLETs on operation-by-operation basis are shown in Table 4.2. Thus, the repair process thoroughness score is:

$$T_{Thrs} = \frac{1}{N_{op}} \sum_{op=1}^{N_{op}} (T_{Thrr})_{op}$$

$$= \frac{1}{8}(0.3 + 0.7 + 0.7 + 0.7 + 0.7 + 0.7 + 0.7)$$

$$= 0.64$$

The normalised value of this and other PLETs' thoroughness score will be found in chapter 5.

PLET option	**PLET operations' thoroughness rating** $(T_{Thrs})_{op}$							
	Pretreatment Logistics	Inspection/ Diagnosis	Dis-assembly	Sorting	Cleaning	Re-condition	Re-assembly	Test & control
Repair	0.3	0.7	0.7	-	0.7	0.7	0.7	0.7
Refurbishing	0.3	0.5	0.5	-	0.5	0.3	0.5	0.5
Remanufacturing	0.1	0.1	0.1	0.1	0.1	0.1	0.1	0.1
Upgrading	0.1	0.3	0.3	0.5	0.3	0.1	0.1	0.1
Cascading	0.5	0.9	0.5	0.5	0.7	0.7	0.9	0.9

Table 4.2: Thoroughness requirement rating of each operation of individual PLET

The diagnosis operation of the shelling machine's repair process is carried out by observation method. That is, by physically observing the shelling machines' performances in terms of the throughput, shelling efficiency, and cleaning efficiency. This involves listening to the sound, looking for loose parts, and using other physical senses. The subjective diagnosis requirement rating of each PLET with regard to the shelling machine will be found in Table 4.3. The repair diagnosis score obtained in comparison with other PLETs by using Table 2.16 and equation 2.51 is:

$T_{dags} \in [0, 1]$ (choose from Table 2.17)

$= 0.7$

PLET option	Product life extension process (PLET) alternatives				
	Repair	Refurbishing	Remanufacturing	Upgrading	Cascading
Required diagnosis rating T_{diags}	0.7	0.5	0.1	0.1	0.9

Table 4.3: Shelling machine diagnosis operations score

The PLETs' disassembly score is obtained by determining the level of the product disassembly required to carryout the process, the variety of connectors that will be removed, the number of each variety/type of connectors that will be remove and the ease with which the specific type of connector can be loosened. The values of these parameters are obtained from Tables 2.18 and 2.19, and substituted into equations 2.52 and 2.53 to arrive at the disassembly score. For instance, the shelling machine repair process disassembly score was obtained as follows: the only one variety of liaisons is encountered, its dissolubility rating, average number of liaison type loosened per product, as well as the level of disassembly requirement by the repair process are bolting, 0.8, 36 and 0.7 respectively. These and similar other PLETs' disassembly parameters are shown in Table 4.4. Effectiveness rating and/or comparative impact rating of the methods are carried out by using Tables prepared for each operation and a PLETs' process operations score are calculated by using appropriate equations. Therefore, the repair disassembly score:

$$(T_{diss})_{12} = [(T_{disrr})(T_{eods})]_{12}$$

$$(T_{diss} = (T_{disrr})[\frac{1}{N_{ltyp}} \sum_{ltyp=1}^{N_{ltyp}} (N_l T_{eodrl})_{ltyp}]$$

$$= (0.7)[\frac{1}{1}(36)(0.8)]$$

$$= 20.16$$

After the normalisation of PLETs' disassembly scores makes the repair process disassembly score become:

$$T_{diss} = 0.173$$

Sorting of parts of the shelling machine in remanufacturing, upgrading and cascading is manual and is based on sight distinction. The sorting score is obtained by using equation 2.54 and Table 2.20 and result of PLET options evaluation for this parameter is shown in chapter 5. As there is no sorting operation in the repair process, the sorting score for remanufacturing process is calculated from equation 2.54 by substituting the sorting parameters values like number of sorting methods (1) and efficiency rating of the employed sorting method for the PLET option (0.9) into it to give:

$$T_{sorts} = \frac{1}{N_{somd}} \sum_{somd=1}^{N_{somd}} (T_{efr})_{somd}$$

$$= \frac{1}{1}(0.9)$$

$$= 0.9$$

Table 4.5 shows the efficiency rating of hand-sorting the shelling machine parts with respect to the specific PLET. Sorting scores for other PLETS are obtainable by using similar procedure.

PLET option	**Remark**	**Liaison/connector type**	
		Bolts and nuts	Welding
Repair	Liaison type dissolution rating T_{eodrl}	0.8	-
	Number of the liaison type per product N_l	36	-
	Required intensity (% of the No. of parts to dismantle to total No. of parts)		0.7
Refurbishing	Liaison type dissolution rating T_{eodrl}	0.8	-
	Number of the liaison type per product N_l	36	-
	Required intensity (% of the No. of parts to dismantle to total No. of parts)		0.1
Remanufacturing	Liaison type dissolution rating T_{eodrl}	0.8	0.1
	Number of the liaison type per product N_l	36	4
	Required intensity (% of the No. of parts to dismantle to total No. of parts)		0.1
Upgrading	Liaison type dissolution rating T_{eodrl}	0.8	0.1
	Number of the liaison type per product N_l	36	4
	Required intensity (% of the No. of parts to dismantle to total No. of parts)		0.3
Cascading	Liaison type dissolution rating T_{eodrl}	0.8	-
	Number of the liaison type per product N_l	36	-
	Required intensity (% of the No. of parts to dismantle to total No. of parts)		0.5

Table 4.4: PLETs' disassembly parameters with regard to the shelling machine

PLET option	Sorting method type *somd* used:	by hand
Repair	Sorting method efficiency rating $(T_{efr})_{somd}$ for the PLET (Repair):	-
Refurbishing	Sorting method efficiency rating $(T_{efr})_{somd}$ for the PLET (Refurbishing):	-
Remanufacturing	Sorting method efficiency rating $(T_{efr})_{somd}$ for the PLET (Remanufacturing):	0.9
Upgrading	Sorting method efficiency rating $(T_{efr})_{somd}$ for the PLET (Upgrading):	0.7
Cascading	Sorting method efficiency rating $(T_{efr})_{somd}$ for the PLET (Cascading):	0.7

Table 4.5: Efficiency rating of hand-sorting the shelling machine parts

Cleaning operation is generally affected by a number of factors, namely: the pH value, temperature and pressure of the cleaning fluid and media. They all affect the efficiency of dirt removal. They may also cause the product materials corrosion, weakness and failure. For this case study, the cleaning scores are calculated by substituting the following parameter values obtained from Tables 2.21, 2.22 and 4.6 into equation 2.55. For repairs, the number of methods used, the efficiency of the method as well as the impact rating of the cleaning method used are: 1, 0.75 and 1 respectively. The repair process cleaning score:

$$T_{cles} = \frac{1}{N_{clmd}} \sum_{clmd=1}^{N_{clmd}} \left(\frac{T_{efr} + T_{impr}}{2}\right)_{clmd}$$

$$= \frac{1}{1}\left(\frac{0.75+1}{2}\right)$$

$$= 0.875$$

For remanufacturing, the number of methods used, the efficiency of the methods as well as the impact rating of the cleaning methods used are: 2; (0.5, 1) and (1, 1) respectively. Thus, the remanufacturing process cleaning score:

$$T_{cles} = \frac{1}{N_{clmd}} \sum_{clmd=1}^{N_{clmd}} \left(\frac{T_{efr} + T_{impr}}{2}\right)_{clmd}$$

$$= \frac{1}{2}\left[\left(\frac{0.5+1}{2}\right) + \left(\frac{1+1}{2}\right)\right]$$

$$= 0.875$$

Other cleaning scores were obtained by the same procedure.

PLET option	Cleaning method type *clmd*:	Compressed air	Dry air (CO_2)
Repair	Cleaning method type's effic. rating $(T_{efr})_{clmd}$ for repair	0.75	-
	Cleaning method type's impact rating $(T_{impr})_{clmd}$ for repair	1.00	-
Refurbishing	Cleaning method type's effic. rating $(T_{efr})_{clmd}$ for refurbishing	0.75	-
	Cleaning method type's impact rating $(T_{impr})_{clmd}$ for refurbishing	1.00	-
Remanufac-turing	Cleaning method type's effic. rating $(T_{efr})_{clmd}$ for remanufacturing	0.50	1.00
	Cleaning method type's impact rating $(T_{impr})_{clmd}$ for remanufacturing	1.00	1.00
Upgrading	Cleaning method type's effic. rating $(T_{efr})_{clmd}$ for upgrading	0.50	1.00
	Cleaning method type's impact rating $(T_{impr})_{clmd}$ for upgrading	1.00	1.00
Cascading	Cleaning method type's effic. rating $(T_{efr})_{clmd}$ for cascading	1.00	-
	Cleaning method type's impact rating $(T_{impr})_{clmd}$ for cascading	1.00	-

Table 4.6: PLETs' cleaning parameters ratings with regard to the shelling machine

The main type of reconditioning activity required by the shelling machine is straightening/ bending. The comparative evaluation of PLETs is made in terms of the intensity of the reconditioning required, the efficiency of the methods used as well as the impacts of the methods. By substituting the repair parameter values in Table 4.7 (obtained by using Tables 2.21, 2.22, and 2.23) into equation 2.56, the shelling machine repair process reconditioning operation score is:

$$
\begin{aligned}
T_{rec} &= T_{recrr}\left[\frac{1}{N_{recmd}}\sum_{recmd=1}^{N_{recmd}}\left(\frac{T_{efr}+T_{imp}}{2}\right)_{recmd}\right] \\
&= (0.5)\left[\frac{1}{1}\left(\frac{0.75+0.82}{2}\right)\right] \\
&= 0.3925
\end{aligned}
$$

PLET option	Reconditioning method type *recmd*:	Straightening /bending
Repair	Recondit'ng method type's effic. rating $(T_{efr})_{recmd}$ for repair	0.75
	Reconditioning method type's impact rating $(T_{impr})_{recmd}$ for repair	0.82
	Required reconditioning intensity rating T_{recrr} for repair	0.50
Refurbishing	Reconditioning method type's effic. rating $(T_{efr})_{recmd}$ for refurbishing	0.75
	Reconditioning method type's impact rating $(T_{impr})_{recmd}$ for refurbishing	0.82
	Required reconditioning intensity rating T_{recrr} for refurbishing	0.10
Remanufacturing	Recondit'ng method type's effic. rating $(T_{efr})_{recmd}$ for remanufacturing	0.50
	Recondit'ng method type's impact rating $(T_{impr})_{recmd}$ for remanufacturing	0.82
	Required reconditioning intensity rating T_{recrr} for remanufacturing	0.10
Upgrading	Reconditioning method type's effic. rating $(T_{efr})_{recmd}$ for upgrading	0.50
	Reconditioning method type's impact rating $(T_{impr})_{recmd}$ for upgrading	0.82
	Required reconditioning intensity rating T_{recrr} for upgrading	0.30
Cascading	Reconditioning method type's effic. rating $(T_{efr})_{recmd}$ for cascading	1.00
	Reconditioning method type's impact rating $(T_{impr})_{recmd}$ for cascading	0.82
	Required reconditioning intensity rating T_{recrr} for cascading	0.50

Table 4.7: PLETs' reconditioning parameter values for the shelling machine

Since reassembly operation is meant to evaluate the reusability of disassembled parts and connectors as well as determine the ease of reassembling, the PLETs are evaluated on these factors with regard to the sheller by using Tables 2.24, 2.25 and 2.26 to prepare Table 4.8 which is consequently used as input to equations 2.57 and 2.58 to arrive at the individual PLET reassembly score. Using repair process and remanufacturing parameter values in Table 4.8 respectively, the repair process reassembly score:

$$
\begin{aligned}
T_{reass} &= (T_{rerr})(R_v) \\
&= (T_{rerr})\left(\frac{1}{N_{voj}}\sum_{jt=1}^{N_{jt}} N_{jt}\left(\frac{T_{eorr}+T_{rurp}}{2}\right)_{jt}\right) \\
&= (0.7)\left(\frac{1}{2}\left[\frac{29}{36}\left(\frac{0.75+1}{2}\right)+\frac{4}{4}\left(\frac{0.05+0.7}{2}\right)\right]\right) \\
&= 0.38
\end{aligned}
$$

For remanufacturing process, the reassembly score:

$$
\begin{aligned}
T_{reass} &= (T_{rerr})(R_v) \\
&= (T_{rerr})\left(\frac{1}{N_{voj}}\sum_{jt=1}^{N_{jt}} \frac{N_{rjt}}{N_{jt}}\left(\frac{T_{eorr}+T_{rurp}}{2}\right)_{jt}\right) \\
&= (0.1)\left(\frac{1}{2}\left[\frac{20}{36}\left(\frac{0.75+1}{2}\right)+\frac{2}{4}\left(\frac{0.05+0.7}{2}\right)\right]\right) \\
&= (0.1)(0.5[0.4861 + 0.1875]) \\
&= 0.03368
\end{aligned}
$$

There are five possible tests that can be carried out on the shelling machine to check if the reworked shelling machine meets the desired functional qualities. Throughput capacity, shelling efficiency, separation efficiency, percentage breakage and functionality are the methods that can be used to assess the quality of output i.e. the sheller whose life has been extended. A repaired sheller is simply tested for the functionality of the faulty part. The question is whether the machine is now shelling and separating or not. The performance evaluation carried out on a refurbished sheller, a remanufactured sheller and an upgraded sheller is more rigorous because it is meant to assess the conformity of the sheller to pre-determined goals. In the case of remanufactured sheller, the performance i.e. the throughput capacity, the shelling efficiency, the percentage breakage, and separation

efficiency must be as new: 450kg/hr, 98%, 4.45%, and 96% respectively. It is assumed that the goal of upgrading the sheller are: to be able to handle multiple grains; simplifying the assembly; reducing percentage breakage to 1%; increasing the throughput capacity, shelling efficiency, and separation efficiency to 500Kg/hr, 99% and 98% respectively.

PLET option	**Remarks**	**Joint/part type** *jt*		
		Bolts & nuts	Snap fits	Welding
Repair	Joint/part type reassembly rating T_{eorr}	0.75	-	0.05
	No. of the joint/part type per prod't N_{jt}	36	-	4
	Joint/part type reusability rating T_{rurp}	1	-	0.7
	Reusable number of the joint/part type per product N_{rjt}	29	-	4
	Reassembly intensity requirement rating T_{rerr}	-	0.7	-
Refurbish-ing	Joint/part type reassembly rating T_{eorr}	0.75	-	0.05
	No. of the joint/part type per prod't N_{jt}	36	-	4
	Joint/part type reusability rating T_{eorr}	1	-	0.7
	Reusable number of the joint/part type per product N_{rjt}	24	-	4
	Reassembly intensity requirement rating T_{rerr}	-	0.1	-
Remanufac-turing	Joint/part type reassembly rating T_{eorr}	0.75	-	0.05
	No. of the joint/part type per prod't N_{jt}	36	-	4
	Joint/part type reusability rating T_{eorr}	1	-	0.7
	Reusable number of the joint/part type per product N_{rjt}	20	-	2
	Reassembly intensity requirement rating T_{rerr}	-	0.1	-
Upgrading	Joint/part type reassembly rating T_{eorr}	0.75	0.65	-
	No. of the joint/part type per prod't N_{jt}	36	4	-
	Joint/part type reusability rating T_{eorr}	1	0.7	-
	Reusable number of the joint/part type per product N_{rjt}	20	4	-
	Reassembly intensity requirement rating T_{rerr}	-	0.3	-
Cascading	Joint/part type reassembly rating T_{eorr}	0.75	-	-
	No. of the joint/part type per prodt N_{jt}	36	-	-
	Joint/part type reusability rating T_{eorr}	1	-	-
	Reusable number of the joint/part type per product N_{rjt}	29	-	-
	Reassembly intensity requirement rating T_{rerr}	-	0.5	-

Table 4.8: PLETs' reassembly parameter values for the shelling machine

Therefore, the sheller is tested for each of these parameters. All these tests are non destructive. They only involve running the machine, varying the configuration of certain parts of the machine and taking the readings. Table 4.9 shows the types and number of tests required by each PLET, the efficiency rating of the test methods in assessing the quality of the reworked machine and impacts of the test methods on the machine. The Table, i.e. Table 4.9, is prepared by using Tables 2.21 and 2.22. This machine does not require modular tests but the test of its complete assembly. Therefore, the modular

variables of equation 2.59 are set equal to one. Thus, the repair process test score for the shelling machine is:

$$T_{tess} = \frac{1}{N_{\text{mod}}} \sum_{\text{mod}=1}^{N_{\text{mod}}} \left(\frac{1}{N_{tesmd}} \sum_{tesmd=1}^{N_{tesmd}} \left(\frac{T_{efr} + T_{imp}}{2} \right)_{tesmd} \right)_{\text{mod}}$$

$$= \frac{1}{1}\left[\frac{1}{1}\left(\frac{1+1}{2}\right)\right]$$

$$= 1$$

For remanufacturing process, the test score:

$$(T_{tess})_3 = \frac{1}{N_{\text{mod}}} \sum_{\text{mod}=1}^{N_{\text{mod}}} \left(\frac{1}{N_{tesmd}} \sum_{tesmd=1}^{N_{tesmd}} \left(\frac{T_{efr} + T_{imp}}{2} \right)_{tesmd} \right)_{\text{mod}}$$

$$= \frac{1}{1}\left[\frac{1}{4}\left\{\left(\frac{1+1}{2}\right) + \left(\frac{1+1}{2}\right) + \left(\frac{1+1}{2}\right) + \left(\frac{1+1}{2}\right)\right\}\right]$$

$$= 1$$

PLET option	**Remarks**	**Testing method type** *tesmd*				
		Through-put	Shelling effic.	% Breakage	Separation efficiency	Function-ality
Repair	Testing method type's effic. rating $(T_{efr})_{tesmd}$ for repair	-	-	-	-	1
	Testing method type's impact rating $(T_{impr})_{tesmd}$ for repair	-	-	-	-	1
Refurbishing	Testing method type's effic. rating $(T_{efr})_{tesmd}$ for refurbishing	-	1	1	1	-
	Testing method type's impact rating $(T_{impr})_{tesmd}$ for refurbishing	-	1	1	1	-
Remanufacturing	Testing method type's effic. rating $(T_{efr})_{tesmd}$ for remanufacturing	1	1	1	1	-
	Testing method type's impact rating $(T_{impr})_{tesmd}$ for remanufacturing	1	1	1	1	-
Upgrading	Testing method type's effic. rating $(T_{efr})_{tesmd}$ for upgrading	1	1	1	1	-
	Testing method type's impact rating $(T_{impr})_{tesmd}$ for upgrading	1	1	1	1	-
Cascading	Testing method type's effic. rating $(T_{efr})_{tesmd}$ for cascading	-	-	-	-	1
	Testing method type's impact rating $(T_{impr})_{tesmd}$ for cascading	-	-	-	-	1

Table 4.9: PLETs' testing parameter values for the shelling machine

This case study machine does not require conventional packaging. Therefore, it is not assessed for packaging. The total score of each PLET alternative for operations factor obtained by using equation 2.61 will be found in chapter 5. For repair process, the operations score is obtained from the equation:

$$T_{opxt} = \sum_{ops=1}^{N_{ops}} T_{ops}$$

$$= [0.7 + 0.173 + 0.875 + 0.3925 + 0.38 + 1]$$

$$= 3.5205$$

By normalising the PLETs' operation scores, the repair process operations score becomes

$$T_{opsc} = 0.53$$

Consequently, the repair process characteristics score:

$$T_{PCXT} = T_{Thrs} + T_{opxt}$$

$$= 0.65 + 0.53.$$

$$= 2.5475$$

This is further normalized across the PLETs before being used to calculate the technical score. The available relevant facility of the firm being considered for this case include: Two electric welding machines, a 5cm plate capacity electric powered shearing machine, a bending machine, two drilling machines, a lathe, a milling machine and a number of hand tools. The firm does not have dry air cleaning facility and suitable press fitting facility but they are available in the neighbourhood. Since the technology of the sheller is simple, the personnel requirements by all the PLET alternatives are available and adequate. Because there is no difference between them, their evaluation is considered unnecessary. The main utility required is electricity which is available in adequate quantity but fails occasionally. By using Table 2.28, the suitability of these resources for reworking the shelling machine is rated for each PLET. For example, the repair process suitability score:

$$T_{resu} = \frac{1}{N_{resutyp}} \sum_{resutyp=1}^{N_{resutyp}} \left(T_{resr}\right)_{typ}$$

$$= \frac{1}{2}[0.9 + 0.9]$$

$$= 0.9$$

Remanufacturing process resource suitability score

$$T_{resu} = \frac{1}{N_{resutyp}} \sum_{resutyp=1}^{N_{resutyp}} (T_{resr})_{typ}$$

$$= \frac{1}{2}[0.9 + 0.75]$$

$$= 0.825$$

These and other PLETs resources suitability scores are shown in Table 4.10.

PLET option	**Resource type's suitability rating** $resr_{typ}$	
	Machinery	Utility
Repair	0.90	0.90
Refurbishing	0.90	0.90
Remanufacturing	0.90	0.75
Upgrading	0.50	0.75
Cascading	0.90	0.90

Table 4.10: PLETs' resource suitability parameters values of the for the shelling machine

As it was not possible to compare product life extension processes of any other firm on the shelling machine, the innovation aspect of the techno-capability factor cannot be assessed. Thus, PLETs techno-capability scores are taken to be the same as their resource suitability scores. Therefore, the repair process techno-capability score:

$$T_{TCAP} = T_{resu}$$

$$= 0.90$$

Having obtained the technical sub-attribute score, each PLET's technical score is calculated by adding up the sub-attribute scores. The normalised results will be found in chapter 5.

4.5.3 PLETs' evaluation on environmental attribute

The environmental evaluation of PLETs with regard to the shelling machine focussed on the resource consumption, waste release and resource conservation/reclamation. Under

resource consumption, the resources considered are non-toxic materials, toxic materials, energy, water, and air/gas. The types of materials used in the construction of the shelling machine are galvanised steel, mild steel, medium carbon steel and rubber. Stainless steel is to be used when upgrading the machine since this is less corrosive than the galvanised steel and the mild steel. The quantity of each of this machine needed to construct a shelling machine from the design and the quantities required for extending the life of the machine by using various alternatives available were estimated. As there are no known legislatively set minimum standard i.e. allowable maximum consumption on these materials, the minimum standard was set by discretion, that the quantity used in extending the life of the product must not be more than the quantity that will be needed in producing the machine from its design. The same procedure was used in the estimation of the minimum energy and other resources consumption. Under resource conservation, as there were no known legislatively set minimum standard i.e. minimum quantity of each resource type to be spared, it is believed that the PLET must be able to spare ten percent of the quantity that will be required to produce the machine from its design. Since none of the materials used during the original manufacture and in the extension of the life is toxic, the modules on toxic material content. and toxic material content reduction were redundant. Table 4.11 shows the estimated materials consumption during various product life extension processes. Using equation 2.36 and Tables 4.11, the total materials consumption per unit product by repair process:

$$q_{MC} = \frac{\sum_{r=1}^{N_r} (q_{rpp})_r}{N_r}$$

$$= \frac{0.3237 + 0.0896 + 0.0156}{3}$$

$$= 0.143 \quad \text{Kg/unit product}$$

PLET option	Galvanised steel	Mild steel	Carbon steel	Rubber
Repair	0.0000	0.3237	0.0896	0.0156
Refurbishing	0.0000	0.3720	0.0960	0.0150
Remanufacturing	3.6568	0.6680	1.1180	0.0150
Upgrading	1.4357	0.3609	2.0504	0.0163
Cascading	0.0000	0.6012	0.0240	0.0000
Allowable maximum consumption	42.0000	39.0000	0.7200	0.1500

Table 4.11: The estimated material type‘s consumption per unit sheller by each PLET

The energy consumption is calculated by estimating the total rate of energy consumption by all facilities being used and the average number of hours of use of these facilities during the period under consideration. Using equation (2.37), the parameters shown in Table 4.12 and 4.13, the repair process energy consumption value:

$$E_{ECV} = (1/N_p)(t_{ec})(E_{ec}) \quad \text{kWh/unit}$$
$$= 1/241(2.8)(308)$$
$$= 3.578\,\text{kWh}$$

PLET option	Estimated total consumption rate by all facilities used for the PLET (kW)	Estimated time of use per period
Repair	2.8	308
Refurbishing	3	396
Remanufacturing	3	465
Upgrading	3	444
Cascading	2	340
Allowable max. consumption per product	1395	

Table 4.12: PLETs' electrical energy consumption parameters for sheller life extension

Repair	Refurbishing	Remanufacturing	Upgrading	Cascading
241	250	250	230	250

Table 4.13: Total numbers of products reworked by the PLET

No water was used during the development of this machine from its design, and no water is used during the rework by any PLET. Thus, the modules on water consumption and on liquid effluents were also inactive. Using equation 2.38 and the parameters in Table 4.14, the repair process air/gas consumption:

$$E_{ARCOSP} = \frac{t_{air} q_{air}}{N_p} \quad \text{Kg/unit}$$
$$= \frac{6(308)}{241}$$
$$= 4.668 \quad \text{Kg/unit product}$$

Other resources use per period is obtained by using the same procedure.

PLET option	Estimated total gas consumption rate (kg/hr) by all facilities used for the PLET	Estimated time (hrs) of use per period
Repair	6	308
Refurbishing	6	396
Remanufacturing	6	465
Upgrading	6	444
Cascading	6	340
Allowable max. consumption per product	2790	

Table 4.14: PLETs' water and gas consumption parameters for sheller life extension

The amount of material resources conserved by carrying out each PLET is calculated by using equations 2.42 and the parameter values in Table 4.15. Thus, the repair process materials conservation score:

$$E_{MCSV} = \sum_{rrmp=1}^{N_{rrmp}} q_{rrmp}$$

$$= \sum_{rrmp=1}^{N_{rrmp}} (q_{rp} - q_{rpp}) \quad \text{Kg/unit}$$

$$= (39.5\text{-}0.312) + (0.750 - 0.086) + (0.080 - 0.080)$$

$$= 39.852 \text{ Kg/unit}$$

Similarly, by using equations 2.43 and 2.44 as well as the parameter values in Table 4.15, energy and gas conserved by the repair process are calculated as followed:

$$E_{EECSV} = E_{Elerpp} - E_{Elecpp} \quad \text{kWh/unit}$$

$$= (6\text{-}3.578)$$

$$= 2.422 \text{ kWh/unit}$$

$$E_{GCSV} = E_{Grpp} - E_{GCSU} \quad \text{Kg/unit}$$

$$= 0.080 - 3.578$$

$$= -3.498 \text{ Kg/unit}$$

The quantities of solid waste and gaseous emissions were estimated for each PLET by using equations 2.45 and Table 4.16. Thus, the total waste released in reworking the shelling machine by the repair process:

$$E_{WR} = E_{SWGFP} + E_{GSEFP} \quad \text{Kg/unit}$$

$$= 0.295 + 0.063$$

$$= 0.358 \text{ Kg/unit}$$

PLET option	Remarks	Resource type						
		Materials					Energy	Others
		Galvan-ised Steel	Mild steel	Carbon steel	Lubri-cant	Rubber	Elect-rical	Gas/ air
	Quantity of resource type required to produce a virgin product	45.000	39.50	0.750	0.080	0.015	6.000	0.080
Repair	Quantity of resource type required to repair the product	0.000	0.312	0.086	0.080	0.000	3.578	3.578
Refurbish-ing	Quantity of resource type required to refurbish the product	0.000	0.312	0.086	0.240	0.000	4.752	4.752
Remanu-facturing	Quantity of resource type required to remanufacture the product	3.657	0.668	1.118	0.240	0.015	2.580	2.580
Upgrading	Quantity of resource type required to upgrade the product	1.436	0.332	0.024	0.450	0.015	2.791	2.791
Cascading	Quantity of resource cascade the product type required to	0.000	0.601	0.024	0.027	0.000	2.720	2.720
Required minimum standard	Required minimum quantity of resource type to be spared	0.450	0.395	0.0075	0.0008	0.0002	0.060	0.0008

Table 4.15: PLETs' resource conservation parameters for sheller life extension

PLET option	Solid waste	Gaseous emissions
Repair	0.295	0.063
Refurbishing	1.107	0.092
Remanufacturing	2.038	0.019
Upgrading	2.044	0.026
Cascading	0.890	0.061
Allowable maximum release	2.038	0.099

Table 4.16: PLETs' waste releases during sheller life extension

Since it is when the toxic elements of waste releases surpasses the threshold values that environmental degradation results, the degree of closeness of elemental releases to the threshold values are used as indicators of environmental impact of the PLETs. Analysis of the waste releases shown in Table 4.16 revealed that the main constituents of the wastes are dust, iron, carbon and zinc. Table 4.17 shows the amount of each of these elements in the waste releases. The environmental impact index of repair process calculated by using equation 2.46 and Table 4.17 is:

$$E_{IMAS} = \frac{1}{N_{wcst}} \sum_{wcst=1}^{N_{wcst}} \left(\frac{\sum_{op=1}^{N_{op}} (q_{wcst})_{op} - LD_{50}}{LD_{50}} \right)_{wcst}$$

$$= \frac{1}{4}\left(\frac{0.311-0.5}{0.5}\right)+\left(\frac{0.201-0.4}{0.4}\right)+\left(\frac{0.007-0.005}{0.05}\right)+\left(\frac{0.003-0.003}{0.003}\right)$$

= 0.25(-0.189 -0.199 -0.043+ 0)

= -0.10775

PLET option	Dust	Iron	Carbon	Zinc
Repair	0.311	0.201	0.007	0.003
Refurbishing	0.300	0.320	0.011	0.006
Remanufacturing	0.300	0.480	0.010	0.004
Upgrading	0.326	0.430	0.089	0.004
Cascading	0.300	0.190	0.006	0.001
LD_{50}	0.500	0.400	0.050	0.003
Allowable maximum release	0.495	0.396	0.0495	0.007

Table 4.17: Constituents of PLETs' waste releases during sheller life extension

Each of these environmental indicators is calculated for all the PLET alternatives by using the same procedure. After normalising each category across the PLET, the results of the consequent calculations will be found in chapter 5.

PLET option	Raw resource consumption values		
	Non-toxic material	Electricity	Air/gas
Repair	0.051	3.670	7.864
Refurbishing	0.091	5.165	10.330
Remanufacturing	1.835	5.671	11.341
Upgrading	9.309	5.481	10.963
Cascading	0.000	2.720	8.160
Max allowable	85.450	6.000	0.080

Table 4.18: Resource consumption by each PLET for sheller life extension

PLET option	Raw resource conservation values		
	Material	Electricity	Air/gas
Repair	84.867	2.330	-3.590
Refurbishing	84.707	0.835	-5.085
Remanufacturing	79.588	0.329	-5.591
Upgrading	83.165	0.519	-5.401
Cascading	84.693	3.280	-2.640
Minimum required	4.500	0.060	0.008

Table 4.19: Resource conservation resulting from using the PLETs for sheller life extension

4.5.4 PLETs' evaluation on market attribute

The comparative evaluation of PLETs' market attribute with regard to the shelling machine was made in terms of the sufficiency of quantitative and qualitative availability of the parts. Other bases of evaluation are materials needed to rework the machine, market quality standard satisfaction by the PLET reworked sheller as well as the sufficiency of the demand for the PLET reworked sheller. Due to the absence of adequate market data, the subjective evaluation tables provided by this work are generally used where it is possible. The availability of all the parts needed to rework the shelling machine at the specific firm site under consideration are in adequate quantity for all the PLETs. And because there is no difference in their evaluation, it is not necessary to include the supply quantity parameter in this assessment. Tables 4.20 and 4.21 show the PLETs ratings in terms of other market parameters. The resulting market sub-attributes scores will be found in the next chapter.

PLET option	**Supply quality M_{SQL}**			
	Workability score M_{woi}	Dim. spec. conf. score M_{dci}	Perf. spec. conf. score M_{pci}	Safety spec. conf. score M_{sci}
Repair	1.50	1.0	0.5	1.5
Refurbishing	1.50	1.0	0.5	1.5
Remanufacturing	0.75	0.5	0.0	1.0
Upgrading	2.00	0.5	1.0	1.5
Cascading	1.50	1.0	0.5	1.5

Table 4.20: PLETs' parts and materials supply scores for the shelling machine

PLET option	M_{DQT}	M_{DQL}		
	Demand volume M_{dvof}	Dimensional conformity index of the product M_{ddci}	Performance conformity index of the product M_{dpci}	Safety conformity index of the product M_{dsci}
Repair	0.3	0.5	0.5	0.5
Refurbishing	0.3	0.5	0.5	0.5
Remanufacturing	0.5	1.0	1.0	1.0
Upgrading	0.7	1.0	1.0	1.0
Cascading	0.5	0.5	0.5	0.5

Table 4.21: PLETs' reworked sheller demand scores

4.5.5 PLETs' evaluation on time attribute

This evaluation involves the determination of how long it takes to rework a Sheller by using the PLET option. This is then compared with the set maximum allowable time. The maximum allowable time may be the customer set time or the sum of the organisational set

time to complete individual operations. Using equations 2.27 to 2.31 along with time data taken, the various times shown in Table 4.22 were arrived at. In this case there was no customer set time. The normalised sub-attributes scores will be found in chapter 5.

PLET option	Raw values				
	Set-up time	Actual operations time	Auxiliary time	Delay time	Summation
Repair	0.3	0.7	0.0	0.2	1.2
Refurbishing	0.3	0.9	0.0	0.3	1.6
Remanufacturing	0.4	1.1	0.1	0.3	1.9
Upgrading	0.3	1.1	0.0	0.2	1.7
Cascading	0.2	0.9	0.0	0.2	1.4
Maximum allowable	0.9	1.7	0.1	0.3	3.0

Table 4.22: PLETs' time attribute scores for the shelling machine

4.5.6 PLETs' evaluation on legislative attribute

This attribute is closely related to the environmental attribute. By using equations 2.32 to 2.34b in conjunction with Tables 4.23 and 4.24 like in the previous attributes shown above, each of the environmental indicator results are compared with environmental legislation requirements in terms of maximum allowable resource type consumption, minimum required resource type conservation/reuse and maximum allowable waste releases as well as maximum allowable impact in order to compute the legislative conformity with such requirements. The results will be found in chapter 5.

PLET option	*NTMCC*	*ENCSC*	*WSRLC*	*WRLIC*
Repair	1.000	0.7104	1.000	0.965
Refurbishing	0.978	0.2546	0.429	0.820
Remanufacturing	0.528	0.1003	0.690	-0.360
Upgrading	0.210	0.1582	-0.690	-0.360
Cascading	0.982	1.0000	0.782	1.000

Table 4.23: PLETs' resources consumption-, waste releases-, and waste release impact conformity to environmental legislation
[*NTMCC* Non-toxic materials consumption conformity score
ENCSC Energy consumption conformity score
WSRLC Waste release conformity score
WRLIC Waste release impact conformity score]

PLET option	*MSVC*	*ENSVC*
Repair	18.859	38.833
Refurbishing	18.824	13.917
Remanufacturing	17.686	5.483
Upgrading	18.481	8.650
Cascading	18.821	54.667

Table 4.24: PLETs' resources conservation conformity to environmental legislation
[*MSVC* Materials savings conformity score
ENSVC Energy savings conformity score]

The performance of the PLET alternatives with regard to the shelling machine on each of the attribute will be found in chapter 5.

4.6 PLETs' evaluation with regard to minimum standards on attributes

It is the permissive set standard that is adopted for this case study because all the PLETs failed to satisfy the minimum gas conservation requirement and this failure is considered to be of insignificant economic and environmental values, such that resetting the minimum standard on such indicator or discarding all the alternatives because of the failure is not necessary.

4.6.1 PLETs' evaluation with regard to minimum standard on cost attribute

Minimum standard set on cost, in this case, is based on maximum allowable cost for some key cost elements. By using equations 2.3 and 2.65b, the resulting departmental costs and their minimum allowable standards are shown in Table 4.25.

PLET option	C_{PTL}	C_{IDG}	C_{DIS}	C_{SRT}	C_{CLE}	C_{RPL}	C_{RIC}	C_{TSE}	Total	Normalised
Repair	187.40	3.91	7.06	-	4.89	4.15	6.94	3.47	217.82	0.9952
Refurbishing	188.61	5.05	9.58	-	5.57	5.38	8.91	4.00	227.10	0.9546
Remanufacturing	191.12	7.38	12.29	4.50	7.94	7.50	28.38	5.20	264.30	0.8202
Upgrading	196.97	6.40	15.08	4.89	10.18	6.53	42.97	6.04	289.05	0.7500
Cascading	187.08	3.19	9.72	3.05	4.58	3.19	3.19	2.78	216.78	1.0000
$(S_{MIN})_{ceb}$	200.00	8.00	16.00	5.00	12.00	8.00	12.00	6.50	267.50	0.8104

Table 4.25: Comparison of PLETs' costs with maximum allowable costs per operation

4.6.2 PLETs' evaluation with regard to minimum standard on technical attribute

In this case, PLETs are assessed on the basis of the ability of the available resources to meet their requirements. The three factors used here are the resources suitability, product complexity and product condition. Given the available technical manpower, machinery and utilities, it is essential to check if the life of product of that complexity and at that condition could be extended by the PLET option. At least, for this to be possible, the available resources must be manageable, and the product complexity should be average or simple. The product condition must not be worse than being manageable for the PLET. Thus, using Tables 2.14, 2.15 and 2.28 as well as equation 2.71, the scores in Table 4.26 are produced. The summation column shows that all the PLETs meet the required minimum standard on technical attribute.

PLET option	Complexity T_{CXT}	Condition T_{PDCD}	Resource suitability T_{resu}	Sum	Normalised score
Repair	0.90	0.90	0.90	2.70	1.000
Refurbishing	0.70	0.90	0.90	2.50	0.926
Remanufacturing	0.50	0.70	0.83	2.03	0.752
Upgrading	0.50	0.70	0.63	1.83	0.678
Cascading	0.90	0.90	0.90	2.70	1.000
Minimum standard	0.50	0.50	0.50	1.50	0.556

Table 4.26: Comparison of PLETs with required minimum on relevant sub-technical attributes.

4.6.3 PLETs' evaluation with regard to minimum standard on environment attribute

The minimum standard in this case is based on every indicator on which the environmental attribute is assessed. The indicators are grouped into positive and negative indicators. The positive indicators consist of resource conservation and toxic material content reduction while the negative indicators are made up of resource consumption, waste release, toxic material consumption and waste release impact. The logic behind the limitations is that the material consumed in extending the life of an existing product must be lower than the quantity required to produce a new one. Similarly, the quantity of other resources consumed in extending the life of a unit product must be less than the quantity required for the manufacture of the new product. Thus the maximum limit placed on resource consumption and toxic material content in this case study is the amount required/used to

manufacture a new one. The waste release and the environmental impact of waste released in the process of extending the lifecycle of the product must be lower than in manufacturing new product. Certain minimum requirements are placed on resource conservation and toxic material content reduction. Using equation 2.70 and Tables 4.16, 4.17, 4.18 and 4.19, the data in Tables 4.27 and 4.28 are produced. Since water, fuel and toxic materials were not used in the production and in the rework of the sheller, they are not included in the evaluation. For all the PLETs, the conservation values are negative because the amount of gas used is more than the amount consumed in the production of new one. This should be understandable because the gas requirement in the manufacturing of sheller is limited to general cleaning while in the case of rework process gas is intensively used to remove the dust, and rust that clung to the product during use. Thus, it is also eliminated from the assessment. Tables 4.27 and 4.28 show the results of the PLETs comparison with the required standards on environmental attribute.

PLET option	**Positive environmental indicators E_{pei}**		
	Materials	Electricity	Air
Repair	0.00	2.42	-3.498
Refurbishing	84.71	1.25	-4.672
Remanufacturing	79.65	0.42	-2.500
Upgrading	0.00	0.21	-2.711
Cascading	84.69	3.28	-2.640
Minimum standard	0.85	0.06	0.0008

Table 4.27: Comparison of PLETs with required minimum on positive environmental indicators.

PLET option	**Negative environmental indicators E_{nei}**				
	Materials (Kg)	Electricity (kW)	Air (Kg)	Wastes (Kg)	Impact score
Repair	0.43	3.58	0.00	0.358	0.52
Refurbishing	0.48	4.75	0.00	1.199	0.64
Remanufacturing	2.46	2.58	0.00	2.057	0.79
Upgrading	3.86	2.79	0.00	2.070	0.85
Cascading	0.63	2.72	0.00	0.951	0.50
Minimum standard	82.35	6.00	0.08	2.137	0.94

Table 4.28: Comparison of PLETs with required minimum on negative environmental indicators.

4.6.4 PLETs' evaluation with regard to minimum standard on market attribute

The setting of minimum standard on market attribute is based on the availability of parts and materials in adequate quantity and quality as well as on the demand volume for the quality of PLET reworked product. Using equation 2.67 and relevant data from Tables 4.20 and 4.21, data in Table 4.29 was produced. Table 4.29 shows that all the PLETs satisfy the set minimum standard on market attribute.

PLET option	M_{SQT}		M_{SQL}			M_{DQT}		M_{DQL}	
	M_{SVL}	M_{woi}	M_{dci}	M_{pci}	M_{sci}	M_{ddci}	M_{ddci}	M_{dpci}	M_{dsci}
Repair	0.70	1.50	1.00	0.50	1.50	0.50	0.50	0.50	0.50
Refurbishing	0.70	1.50	1.00	0.50	1.50	0.50	0.50	0.50	0.50
Remanufacturing	0.50	0.75	0.50	0.00	1.00	1.00	1.00	1.00	1.00
Upgrading	0.30	2.00	0.50	1.00	1.50	1.00	1.00	1.00	1.00
Cascading	0.90	1.50	1.00	0.50	1.50	0.50	0.50	0.50	0.50
Minimum standard	0.50	1.53	0.50	0.50	1.00	0.50	0.50	0.50	0.50

Table 4.29: Supply of parts and materials required for the product rework by PLET

4.6.5 PLETs' evaluation with regard to minimum standard on time attribute

The minimum time standard used in this case is the maximum allowable time on individual operations making up the PLET. From the results shown in Table 4.22 which were produced by using equation 2.68, it can be seen that all the PLETs met the set time standard.

4.6.6 PLETs' evaluation with regard to minimum standard on legislative attribute

The evaluation of the PLETs with regard to meeting minimum legislative standard is only required if the basis of legislative attribute evaluation of PLETs have been carried out on desired condition. Since the basis of legislative evaluation in this case has been on mandatory condition, before any PLET can be acceptable it must satisfy all the mandatory legislations. The PLET(s) that satisfied this condition will be found in chapter 5.

The summary of the normalised PLETs' scores in comparison with the minimum standard on each of the attributes and the overall scores will be found in chapter 5.

5 Results and Discussion

Having obtained the relevant data on the shelling machine with regard to the various life extension opportunities and substituting them into various mathematical expressions making up the decision model, this chapter shows major results of the evaluations and their explanations.

5.1 Analyses of results of PLETs' evaluation on each attribute

This section shows the results of PLETs' assessment on each attribute with the aim of evaluating the PLET selection on the basis of individual attribute discussed and to analyse the relevance of some sub-attributes on PLET selection. The sensitivity analyses of all attributes except environmental attribute are carried out by observing the percentage change in each PLET's score on the attribute resulting from the percentage changes in the corresponding sub-attributes. However, changes in actual environmental score of each PLET resulting from percentage changes in environmental sub-attributes are used, instead of percentage changes in PLET's environmental score, purposely to demonstrate how the two methods can be used in obtaining different information from the sensitivity analyses.

5.1.1 Analysis of PLETs' evaluation results on cost attribute

Table 5.1 shows the various product life extension processes and their expected costs in categories. This result revealed that the least process cost is incurred when cascading is used. This is followed by the repair process. This result is justifiable because least quantity of resources are employed during cascading. Looking at Table 5.2, one can see that all the PLETs satisfied the maximum allowable departmental cost except remanufacturing and upgrading. These two processes exceeded the allowable departmental cost at the reassembly stage of product rework.

PLET option	**Costs per unit product reworked**										**Normali-sed C_{PLET}**
	C_{DM}	C_{DL}	C_{FO}	C_{DRT}	C_{CVS}	C_{FTR}	C_{AO}	C_{RWD}	C_{SO}	C_{GSD}	
Repair	180.00	11.13	26.70	191.13	37.82	217.82	9.56	227.38	9.56	236.94	0.9870
Refurbishing	180.00	15.52	31.58	195.52	47.10	227.10	9.78	236.88	9.78	246.65	0.9475
Remanufacturing	197.68	19.14	47.48	216.82	66.62	264.30	15.18	279.48	15.18	294.66	0.8030
Upgrading	211.51	14.99	62.56	226.49	77.54	289.05	13.59	302.64	13.59	316.23	0.7416
Cascading	180.00	11.25	25.53	191.25	36.78	216.78	7.65	224.43	9.56	233.99	1.0000

Table 5.1: Comparison of unit costs of PLETs in terms of individual cost factors
[C_{RWD} Cost of reworked good C_{GSD} Cost of goods sold]

PLET option	C_{PTL}	C_{IDG}	C_{DIS}	C_{SRT}	C_{CLE}	C_{RPL}	C_{RIC}	C_{TSC}	Total cost	Normalised score
Repair	187.40	3.91	7.06	-	4.89	4.15	6.94	3.47	217.82	0.995
Refurbishing	188.61	5.05	9.58	-	5.57	5.38	8.91	4.00	227.10	0.955
Remanufacturing	191.12	7.38	12.29	4.50	7.94	7.50	28.38	5.20	264.30	0.820
Upgrading	196.97	6.40	15.08	4.89	10.18	6.53	42.97	6.04	289.05	0.750
Cascading	187.08	3.19	9.72	3.05	4.58	3.19	3.19	2.78	216.78	1.000
$(S_{MIN})_{ceb}$	200.00	8.00	16.00	5.00	12.00	8.00	12.00	6.50	267.50	0.810

Table 5.2: PLET costs and cost elements based minimum standards (per unit reworked product)

In evaluating the effect of changes in major cost elements, four main operations of PLETs were selected on the basis of the amount of resources committed to them. Figure 5.1 shows, for this test case, that changes in pre-treatment logistics cost results in linear changes in cost of each of the processes.

Furthermore, assuming the logistics cost changes from the present value by any percentage both repair and cascading costs will be the most affected while upgrading cost will be least affected.

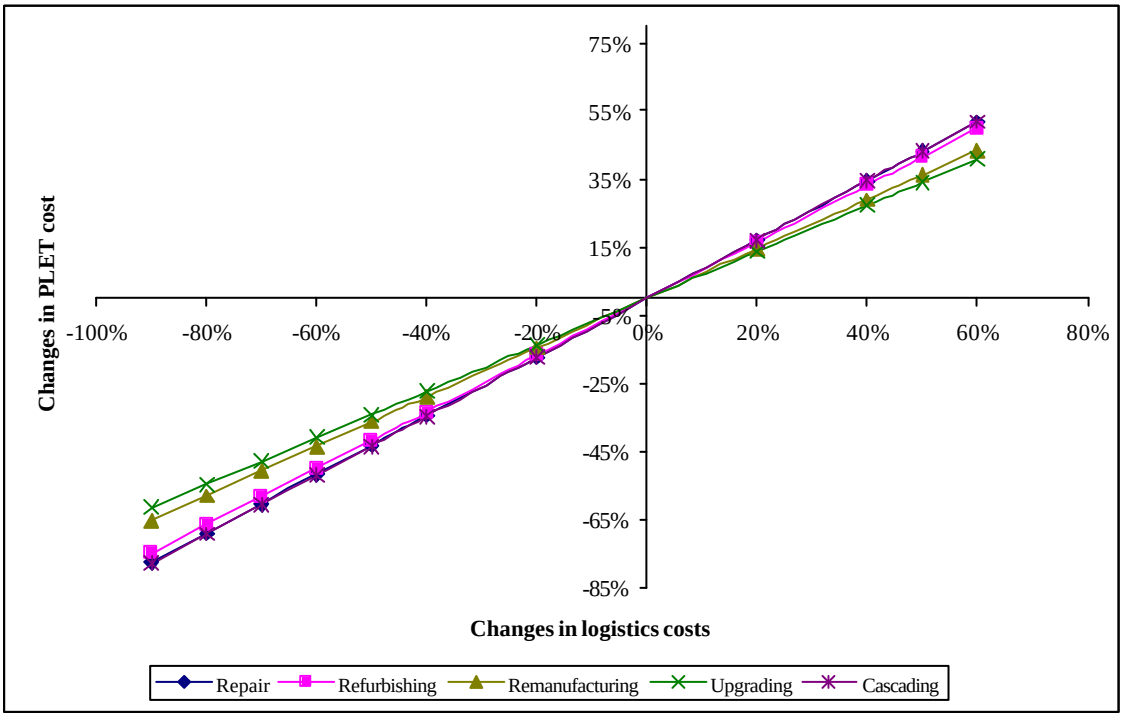


Figure 5.1: Sensitivity of PLET cost to changes in logistics costs

Figure 5.2 shows similar linear response of PLETs costs to changes in disassembly costs just as in pre-treatment logistics costs in Figure 5.1. However, changes in disassembly cost make upgrading cost the most affected and repair process cost the least affected.

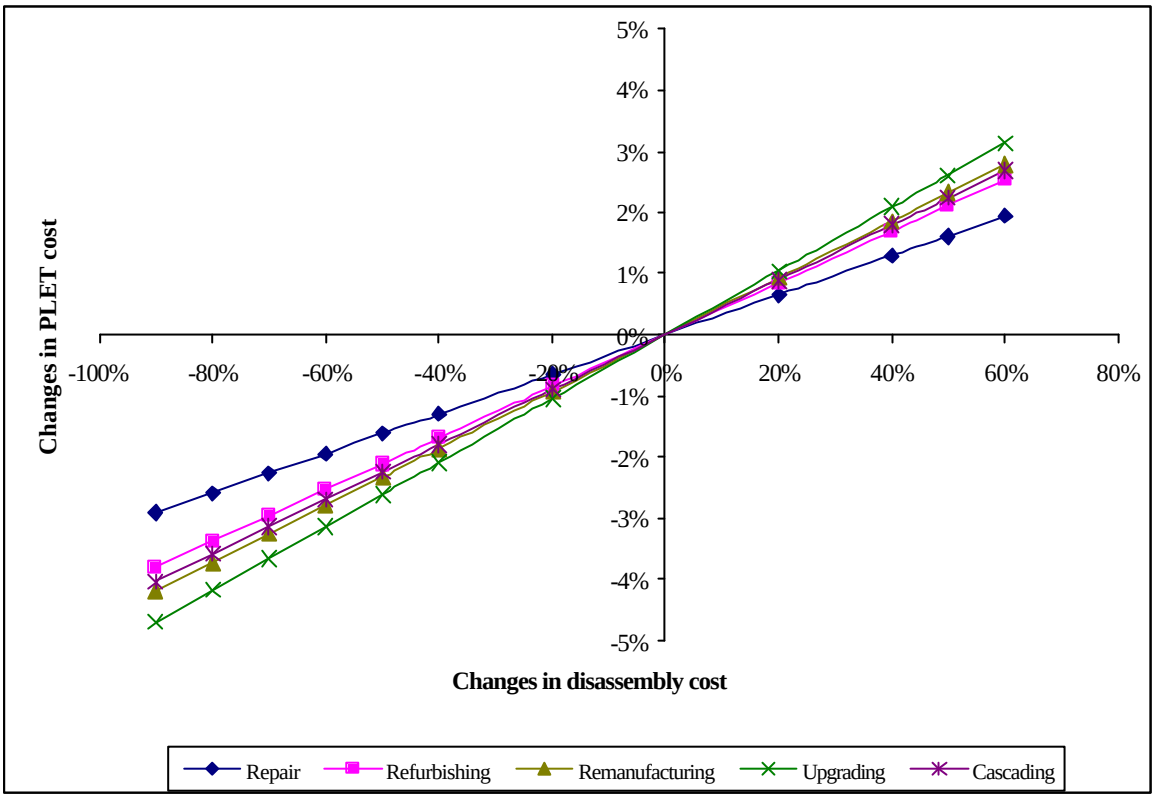


Figure 5.2: Sensitivity of PLET cost to changes in disassembly cost

Moreover, similar pattern of linear changes in PLETs costs to the ones in Figures 5.1 and 5.2 can be observed when changes occur in cleaning costs (Figure 5.3). From Figure 5.3, one can see that if the cost of cleaning operation increases from the present value for each PLET by any percentage, upgrading process cost will be the most affected PLET and cascading will be the least affected.

Just like in Figures 5.1, 5.2 and 5.3, the process cost graphs are also linear under changing reconditioning cost (Figure 5.4). In this case, the graph of the upgrading process cost is non-linear when the reconditioning cost decreases. As the reconditioning costs changes from the present value, remanufacturing process emerges as the most affected PLET while cascading is the least affect PLET.

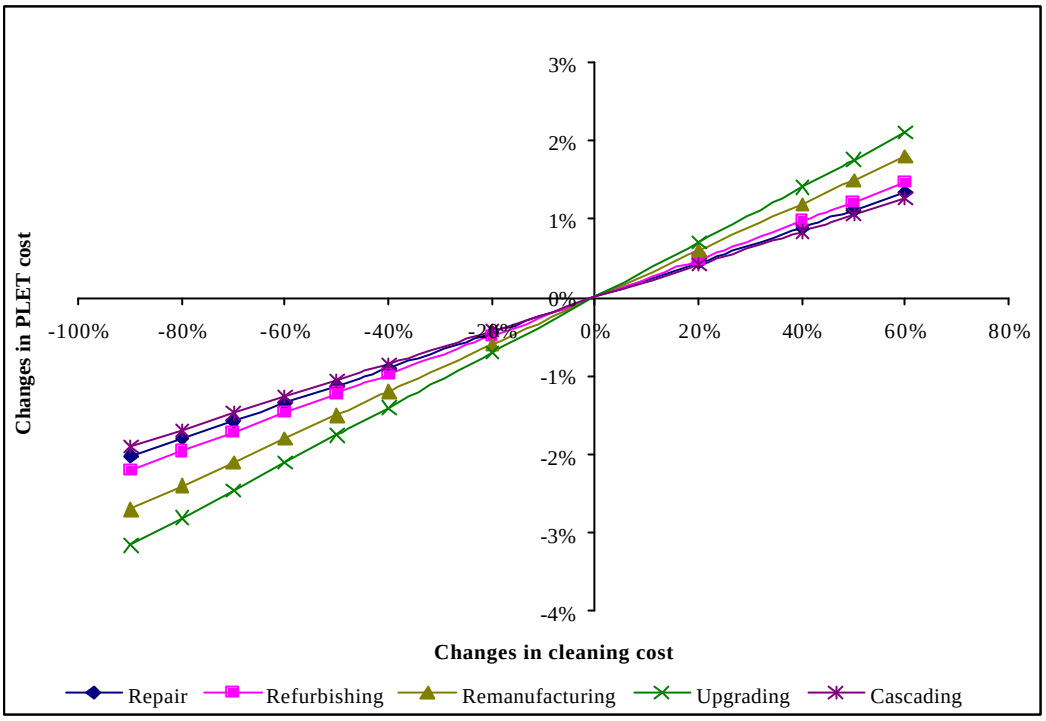


Figure 5.3: Sensitivity of PLETs costs to changes in cleaning costs

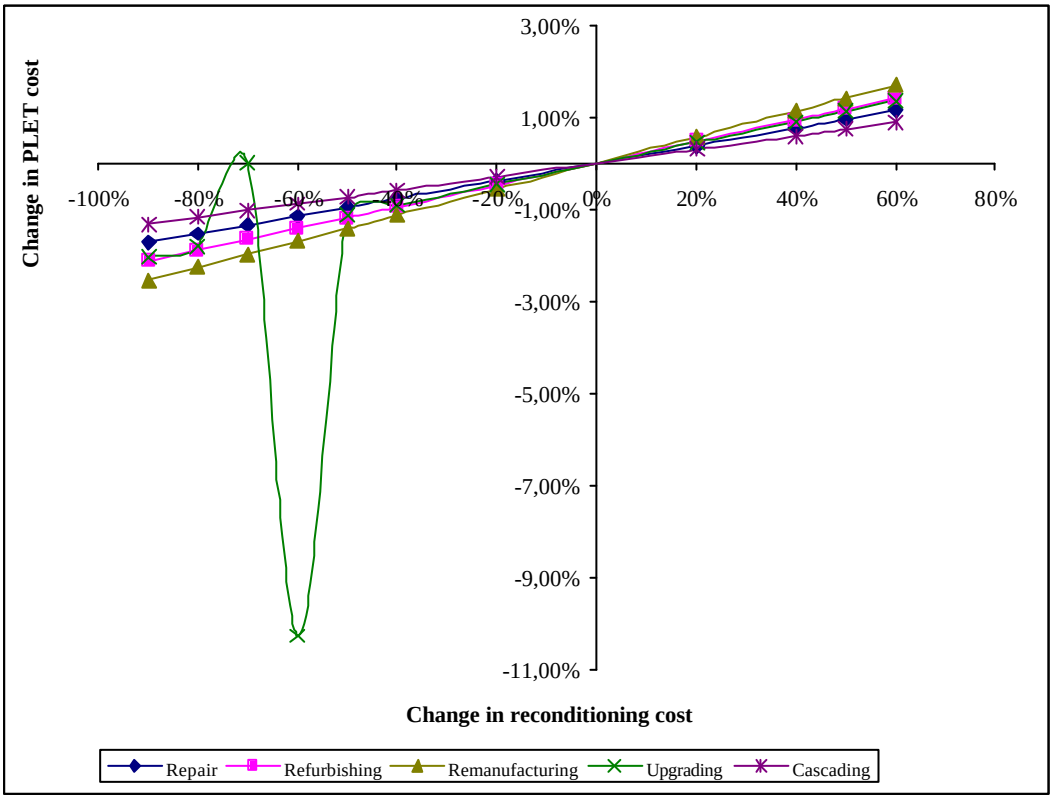


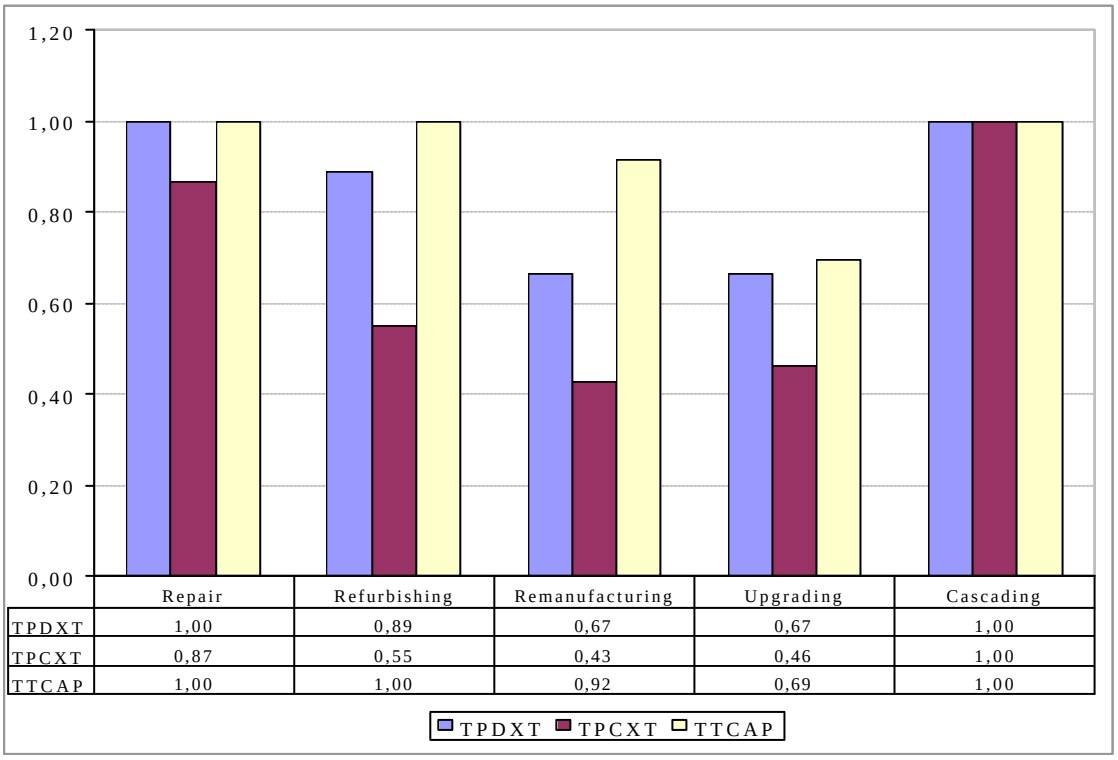
Figure 5.4: Sensitivity of PLETs costs to changes in reconditioning costs

From Figure 5.1, it could be noted that 20% change in logistics costs of each PLET results in about 15% change in the PLET cost while similar changes in disassembly cost (Figure 5.2) only results in between 0.5% (for repairs) and 1%(for upgrading) changes in

PLET costs. Furthermore, from Figure 5.3 one can see that for every 20% changes in cleaning costs there is between about 0.3% (for cascading and repair) to about 0.7% (for upgrading) change in PLETs costs while Figure 5.4 shows that for every 20% change in reconditioning cost, PLETs costs changes by between 0.25% (for cascading) and 0.6% (for remanufacturing. From these trends in changes of PLETs cost due to changes of major cost elements, it can be concluded that logistics cost have overriding influence on the shelling machine's life extension cost. Another look at Figures 5.1 –5.4 also show that while cascading process cost is least affected by changes in the main cost elements, upgrading process cost is the most affected. From Table 5.2, one can also conclude that product life extension cost of the shelling machine can be drastically reduced by reducing the pre-treatment logistics costs.

5.1.2 Analysis of PLETs evaluation results on technical attribute

In comparison with other PLETs, Figure 5.5 shows that cascading process has the highest technical scores. This results indicate that it is not only that the resources available is best suited for cascading, but the sheller configuration and condition favour adopting cascading process for extending the sheller lifecycle. Furthermore, Table 5.3 shows that all the PLETs satisfied the minimum technical requirement for the sheller's lifecycle extension.



	Repair	Refurbishing	Remanufacturing	Upgrading	Cascading
TPDXT	1,00	0,89	0,67	0,67	1,00
TPCXT	0,87	0,55	0,43	0,46	1,00
TTCAP	1,00	1,00	0,92	0,69	1,00

Figure 5.5: PLETs' performances on technical sub-attribute

PLET option	Complexity T_{CXT}	Condition T_{PDCD}	Resource suitability T_{resu}	Normalised score
Repair	1.00	1.00	1.00	1.00
Refurbishing	0.78	1.00	1.00	0.93
Remanufacturing	0.56	0.78	0.92	0.75
Upgrading	0.56	0.78	0.69	0.68
Cascading	1.00	1.00	1.00	1.00
Minimum standard	0.5	0.5	0.5	0.50

Table 5.3: Comparison of PLETs with required minimum on relevant sub-technical attributes.

With regard to the sensitivity of PLETs' technical attribute scores to changes in technical sub-attributes scores, Figure 5.6 shows that changes in product characteristics scores result in linear changes in PLETs' technical attribute graphs and that the graphs of the PLETs are very close. It means that there are proportional changes in technical score with changes in product characteristics scores and that the differences in PLETs' requirements with regard to product complexity and condition are very small. This Figure also shows that upgrading and refurbishing processes are mostly affected by changes in product characteristics while remanufacturing and cascading are least affected by the same change.

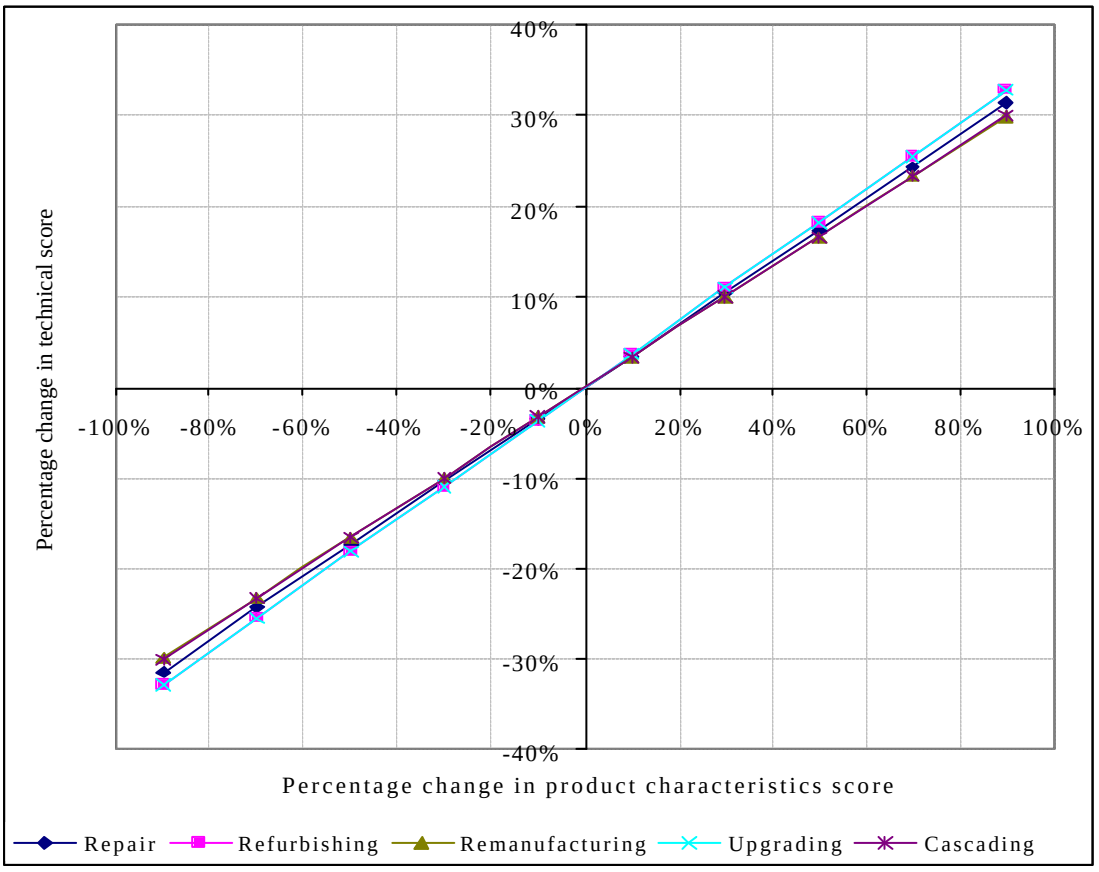


Figure 5.6: Sensitivity of PLETs' technical scores to changes in product characteristics scores

Moreover, Figure 5.7 shows that decrease in the process characteristics score from the present value causes linear changes in technical attribute graphs. However, increase in process characteristics score results in parabolic change in PLETs' technical attribute scores graphs. It could be observed that the parabolic change in repair and refurbishing graphs are concave in nature while the rest are convex. The implication of the linearity is that reduction in thoroughness requirement of the constituent PLETs' operations and in the number of operations results in lower requirement for technical resources.

This Figure further shows that remanufacturing is mostly affected by decrease in process characteristics but the chaotic behaviours of the PLETs' graphs on the side of increase in process characteristics makes it inconclusive.

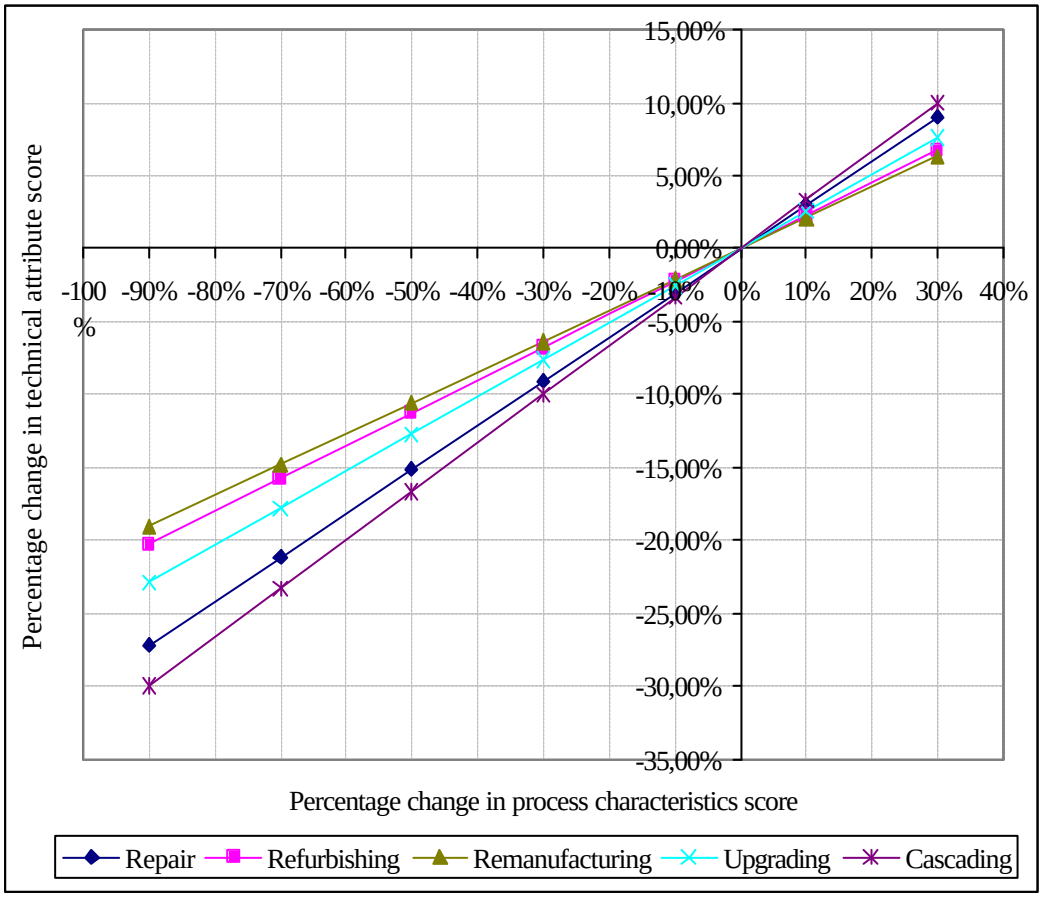


Figure 5.7: Sensitivity of PLETs' technical scores to changes in process characteristics scores

PLETs' technical scores graphs in Figure 5.8 show similar behaviour to changes in techno-capability scores as in Figure 5.7 except that the gradient of the graphs in Figure 5.8 is

higher than in Figure 5.9. One can conclude here that changes in techno-capability score have similar influence on PLETs as changes in process characteristics score but that the severity of the effect of changes in techno-capability is higher than that of changes in process characteristics.

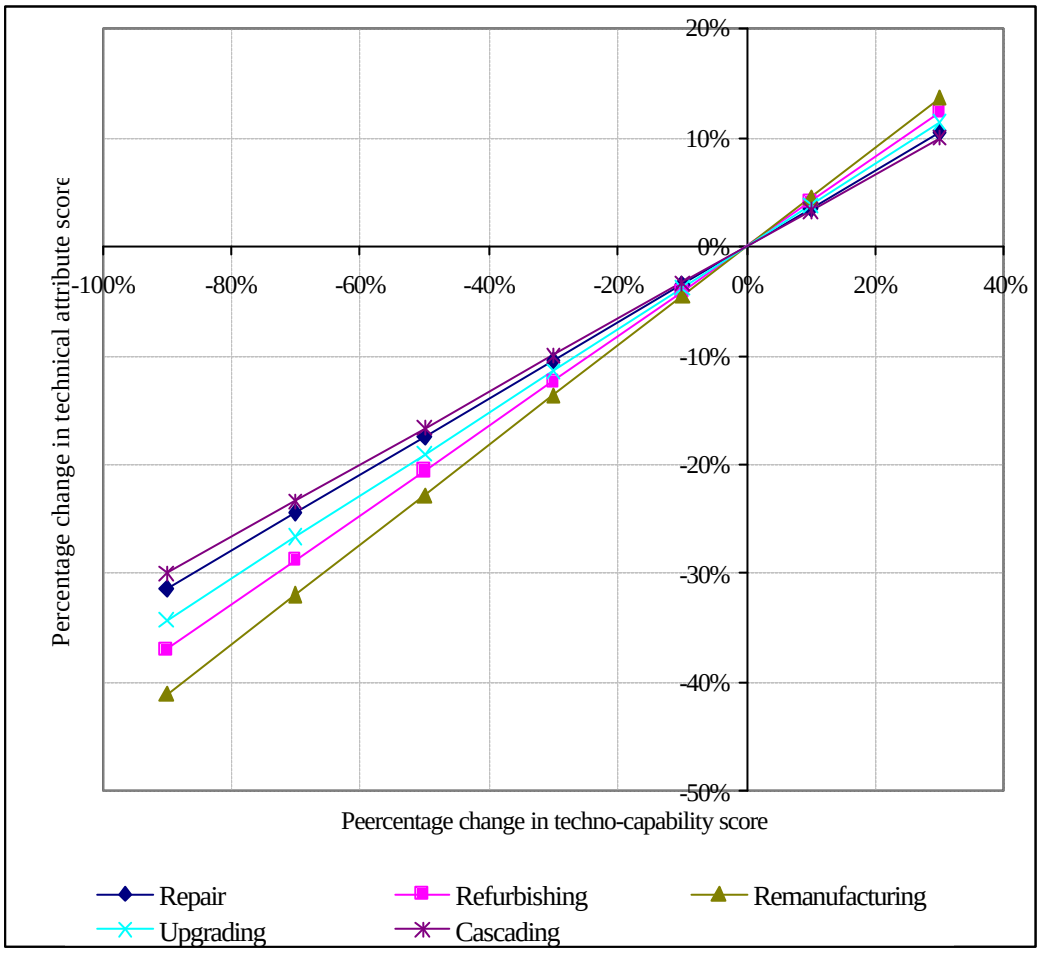


Figure 5.8: Sensitivity of PLETs' technical scores to changes in techno-capability scores

Looking at each of the Figures 5.6, 5.7 and 5.8 in turn, one notes that 30% change in product characteristics score of each PLET (in Figure 5.6) results in about 10% change in the PLETs' technical scores. Similar changes in process characteristics scores (on the reduction side of Figure 5.7) results in between 5% (for remanufacturing) and 10% (for cascading) changes in PLET costs. Furthermore, from Figure 5.8 one can also see that for every 30% decrease in techno-capability scores there is between about 9% (for cascading)

to about 15% (for remanufacturing) change in PLETs technical score. From these results one can conclude that each of the three technical sub-attributes have similar influence on technical attribute score.

5.1.3 Analysis of PLETs' evaluation on environmental attribute

While Table 5.4 shows comparative resource consumption by each PLET, Table 5.5 shows the comparative resource savings by the PLETs. Furthermore, Table 5.6 shows the waste releases by each PLET. From these Tables, one can see that all PLETs satisfied the minimum standards on materials (except in lubricant consumption) and energy consumption. All the processes failed to meet the set minimum requirement on air/gas consumption. The failure is vividly shown by the negative scores under resource savings in Table 5.5. This failure is understandable, because more air/gas is required for cleaning operation in reworking the shelling machine than in manufacturing. Moreover, Table 5.6 shows that all the processes satisfied the minimum standards on waste releases and that repair process released the least quantity of waste. In addition, Table 5.7 indicates the environmental impact of each PLET. The negativity of the values in this table (i.e. Table 5.7) shows that the impacts of the waste released are below the threshold values. The totality of the environmental evaluation of the processes ranked repair as the best PLET for the shelling machine (see Figure 5.6).

PLET option	**Normalized resource consumption values**			
	Non-toxic material	Electricity	Air/gas	E_{RSCM}
Repair	0.000019665	0.741187384	0.010173160	0.373857470
Refurbishing	0.000010952	0.526599327	0.007744108	0.265873890
Remanufacturing	0.000000545	0.479655914	0.007053763	0.242168013
Upgrading	0.000000107	0.496216216	0.007297297	0.250528728
Cascading	1.000000000	1.000000000	0.009803922	1.000000000
Max allowable	0.000000012	0.453333333	1.000000000	0.723121957

Table 5.4: Normalized resource consumption values and resource consumption score [E_{RSCM} Resource consumption score]

PLET option	Normalized conservation values			Sum	E_{RCSV}
	Material	Electricity	Air/gas		
Repair	1.0000	0.7104	-0.0022	1.7082	1.0000
Refurbishing	0.9981	0.2545	-0.0016	1.2510	0.7324
Remanufacturing	0.0622	0.8996	-0.0014	0.9604	0.5622
Upgrading	0.9800	0.1581	-0.0015	1.1366	0.6654
Cascading	0.0020	1.0000	-0.0030	0.9990	0.5848
Minimum required	0.0530	0.0183	1.0000	1.0713	0.6272

Table 5.5: Normalized resource conservation values
[E_{RCSV} Resource consumption score]

PLET option	Total waste	E_{WR}
Repair	0.358	1.000
Refurbishing	1.199	0.299
Remanufacturing	2.057	0.174
Upgrading	2.07	0.173
Cascading	0.951	0.376
Max allowable release	2.137	0.168

Table 5.6: Material wastes resulting from individual PLETs

PLET option	Environmental impact of waste constituent type *wcst* released by the PLET				Sum	E_{WRI}
	1	2	3	4		
Repair	-0.362	-0.498	-0.860	-0.067	-1.786	0.753
Refurbishing	-0.348	-0.200	-0.780	-1.000	-2.328	0.982
Remanufacturing	-0.390	-0.200	-0.800	-0.433	-1.824	0.769
Upgrading	-0.383	-0.075	-0.780	-0.367	-1.604	0.677
Cascading	-0.400	-0.525	-0.880	-0.567	-2.372	1.000
Minimum standard	-0.010	-0.010	-0.010	-1.333	-1.363	0.575

Table 5.7: Impact indices of PLET released wastes
[E_{WRI} Waste release impact score]

PLET option	E_{RCSM}	E_{WR}	E_{WRI}	E_{RCSV}	Sum	E_{PLET}
Repair	0.356	1.000	0.753	1.000	3.109	1.000
Refurbishing	0.253	0.299	0.982	0.732	2.266	0.729
Remanufacturing	0.231	0.174	0.769	0.562	1.736	0.558
Upgrading	0.239	0.173	0.676	0.665	1.753	0.564
Cascading	1.000	0.376	1.000	0.585	2.961	0.952
Mini standard	0.690	0.170	0.570	0.63	2.060	0.662

Table 5.8: Comparison of environmental indicators with the minimum standards

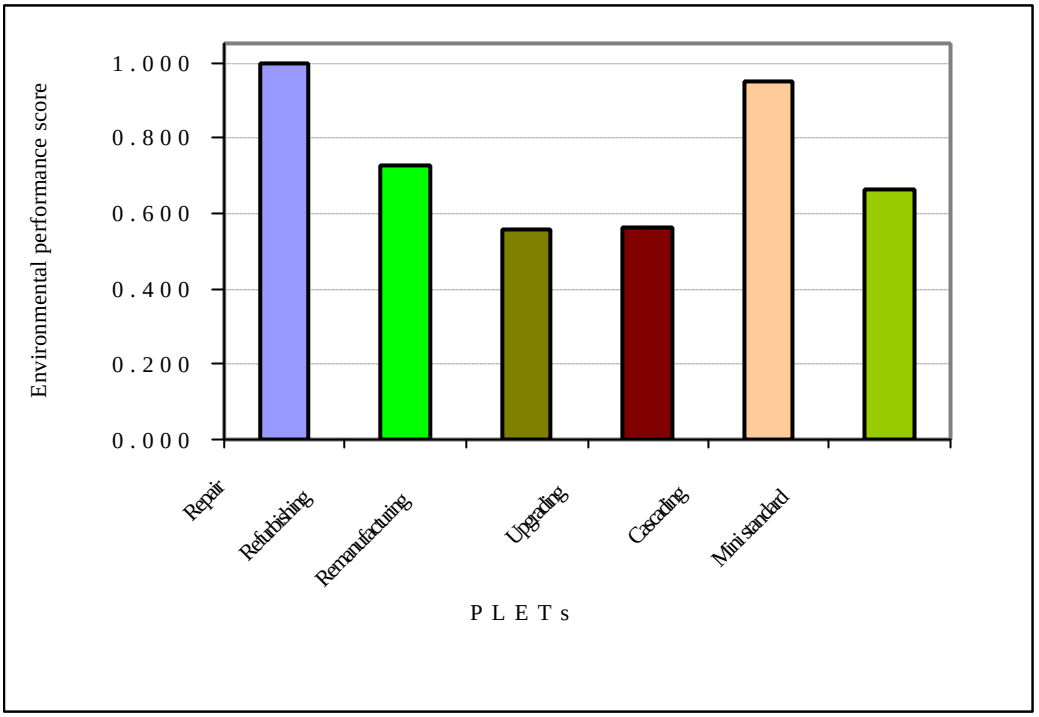


Figure 5.9: PLETs' performances on environmental attribute

On the sensitivity of PLETs environmental scores to changes in the environmental sub-attributes, Figure 5.10 shows that increases in resource consumption score (i.e. decrease in resource consumption) from the present level by any percentage up to 22% results both in PLETs environmental scores increase and in the choice of repair process. It also shows that cascading process is recommended if further reduction in resource consumption is desired. Moreover, the Figure shows that decrease in resource consumption score (i.e. increase in resource consumption) still favours the adoption of repair process for sheller life extension under environmental consideration. The preference for repair and cascading can be understandable in that resource consumption by other PLETs is relatively high and environmental consideration supports low resource consumption.

Figure 5.11 shows the influence of change in waste release on environmental attribute score. One can see here that the environmental scores of all the PLETs except repairs decreases linearly as the waste release scores changes from the present level (0%) through to 90%. Except between 19% and 32% as well as between 82% and 90% decreases in waste release scores when cascading has the highest scores, repair remain the most environmentally preferred process throughout the changes in waste releases. It can be

observed that when the waste release score decreases the PLETs graphs become non-linear.

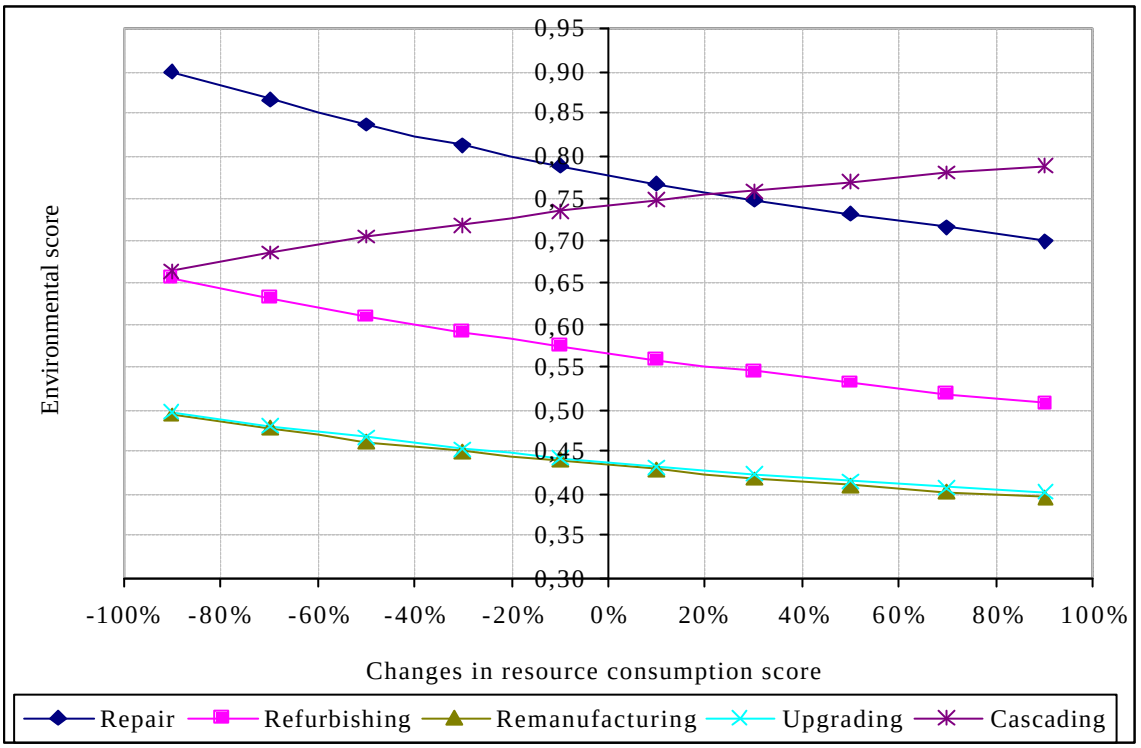


Figure 5.10: Sensitivity of PLETs' environmental score to change in resource consumption score

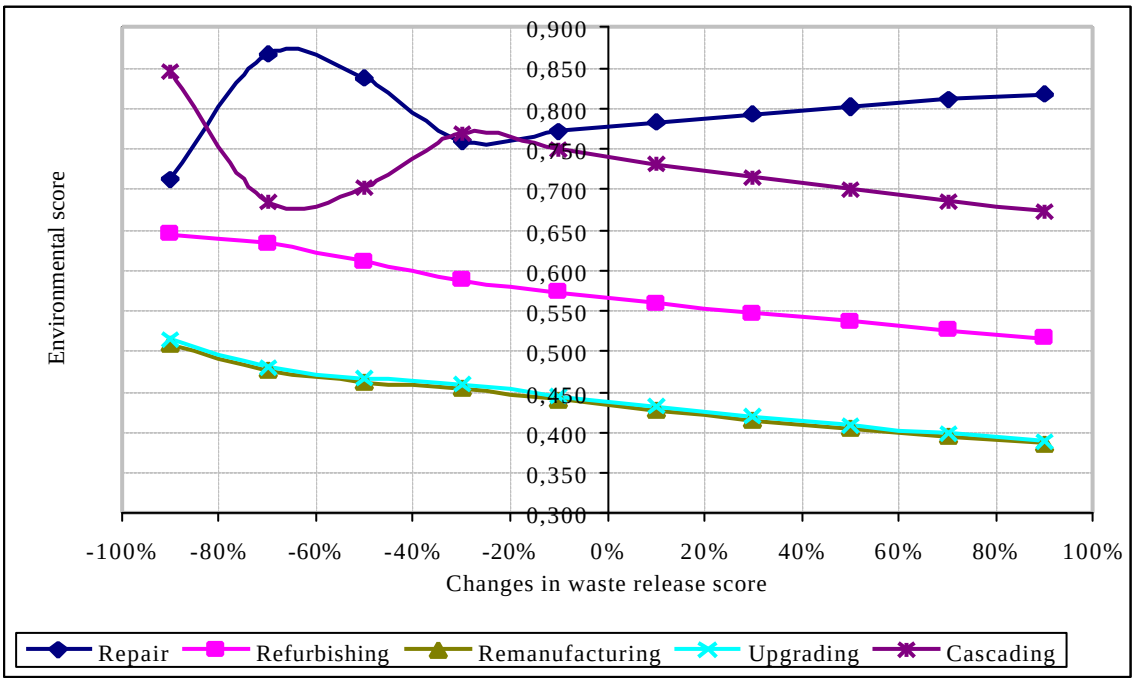


Figure 5.11: Sensitivity of environmental score of PLETs to changes in waste release score

Furthermore, Figure 5.12 shows that decrease in waste release impacts score from the present value by any percentage does not affect the choice of PLET. And that it is only increase in the waste release impact score (i.e decrease in waste release impact) from the present value up to about 60% that results in the preference changes from repair to cascading process. A sharp decrease in environmental score of all the PLETs can also be observed when waste release impact score decreases from 70%.

Moreover, one can observe in Figure 5.13 that increase in resource conservation score (i.e increase in resource savings) from the present level by any percentage does not change the preference for repair as the best PLET. However, decrease in resource savings scores by any percentage from about 37% results in preference for cascading process.

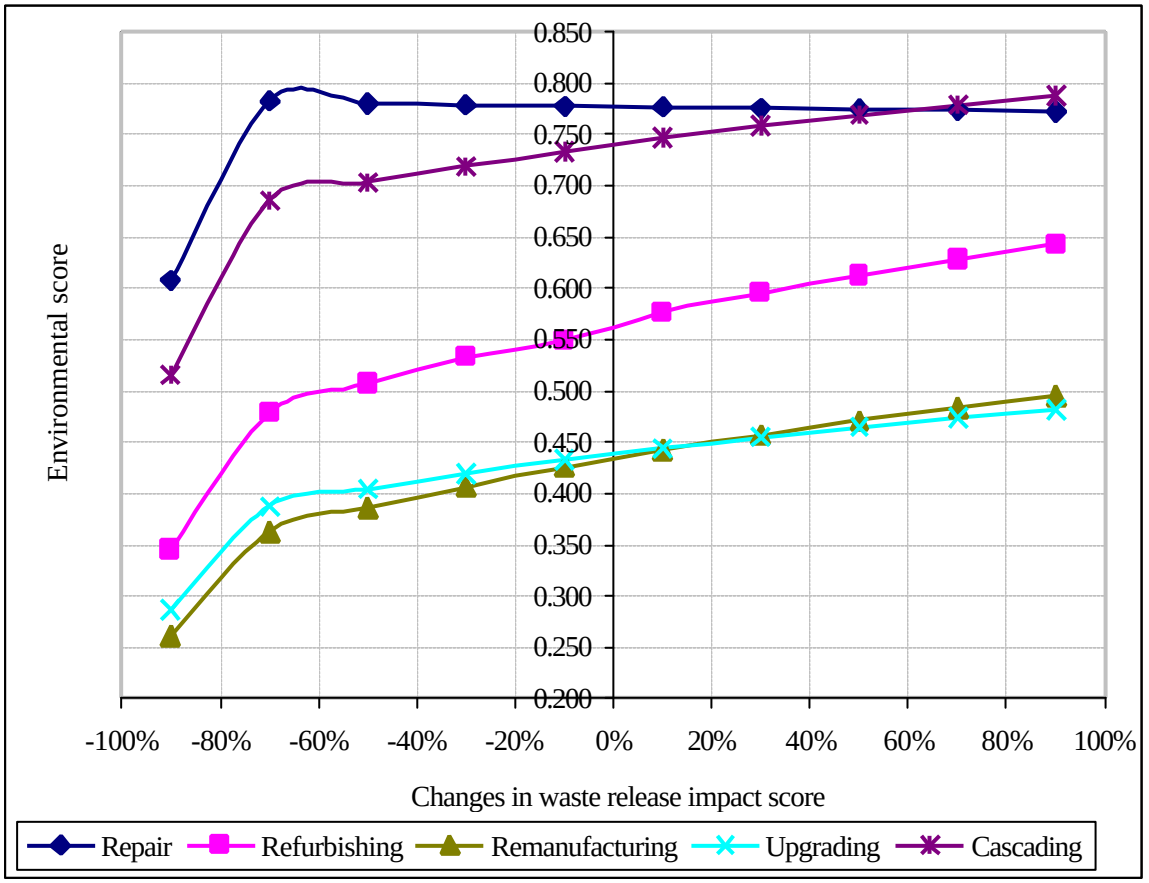


Figure 5.12: Sensitivity of PLET's environmental score to changes in waste release impact score

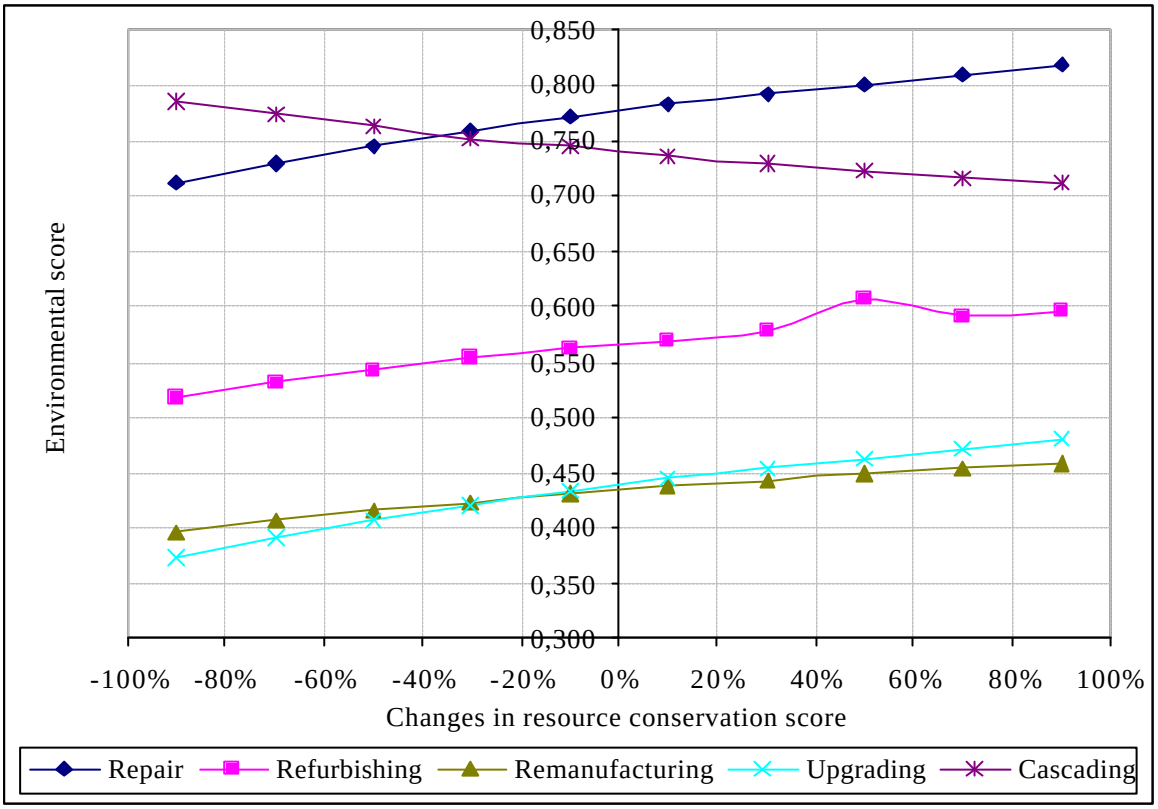


Figure 5.13: Sensitivity of PLET's environmental score to change in resource conservation score

5.1.4 Analysis of PLETs' evaluation on market attribute

The results of the comparative evaluations of PLET in terms of parts supply and reworked product demand shown in Tables 5.9 and Figure 5.14 identified upgrading process as the best PLET. This arose not only from the availability of large quantity and quality of parts required for reworking the sheller but high quantitative and qualitative demand for upgraded shelling machine.

PLET option	M_{SQT}	M_{SQL}	M_{DQT}	M_{DQL}	**Sum**	M_{PLET}
Repair	1.000	0.900	0.429	0.500	2.829	0.707
Refurbishing	1.000	0.900	0.429	0.500	2.829	0.707
Remanufacturing	1.000	0.450	0.714	1.000	3.164	0.791
Upgrading	1.000	1.000	1.000	1.000	4.000	1.000
Cascading	1.000	0.900	0.714	0.500	3.114	0.779
Minimum standard	1.000	0.706	0.714	0.500	2.920	0.730

Table 5.9: PLET's performance comparison with minimum standard on market attribute [M_{SQT} Supply quantity score M_{SQL} Supply quality score M_{SQL} Supply score M_{DQT} Demand quantity score M_{DQL} Demand quality score M_{DQL} Demand score M_{PLET} Market score]

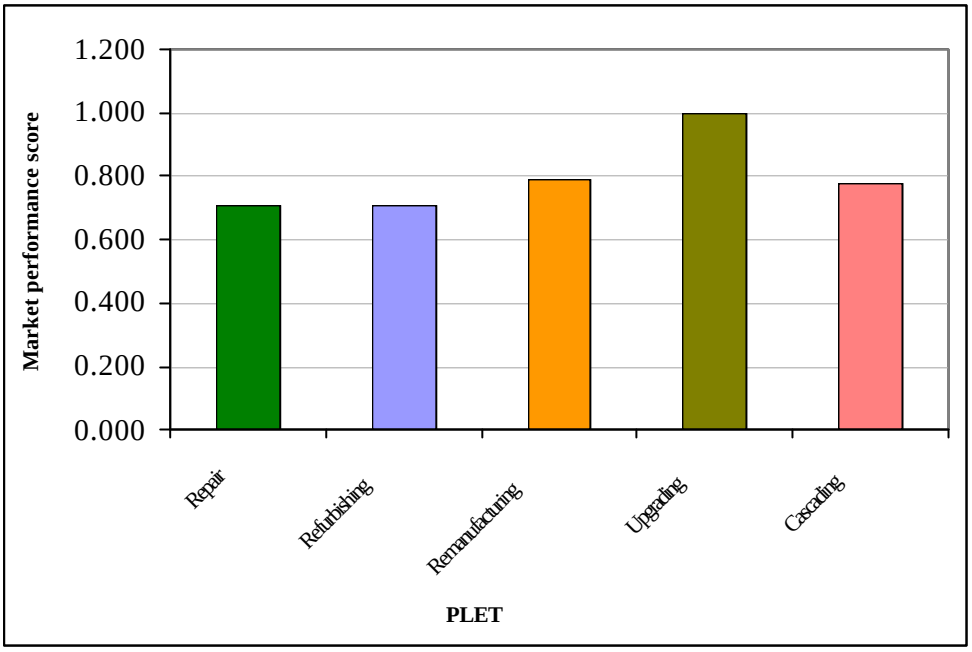


Figure 5.14: Market attribute scores comparison

The sensitivity of PLETs' market scores to changes in market sub-attributes is shown by Figures 5.15-5.18. Figure 5.15 shows that refurbishing is the most affected PLET and that upgrading process is least affected by changes in supply quantity.

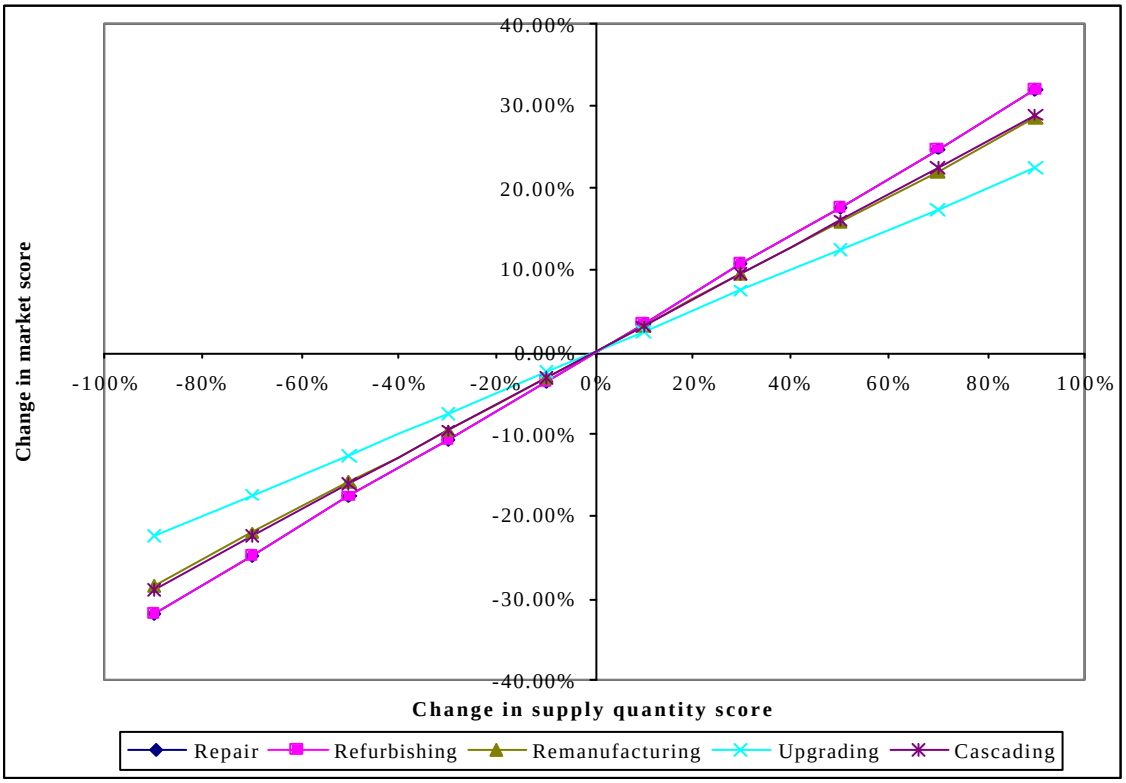


Figure 5.15: Sensitivity of PLETs' market score to change in supply quantity score

Furthermore, it can be seen from Figure 5.16 that refurbishing market score is the most affected by changes in supply qualities while upgrading is least affected. Figure 5.17 also shows that market score of upgrading process is the most affected by changes in demand quality score while refurbishing is the least affected.

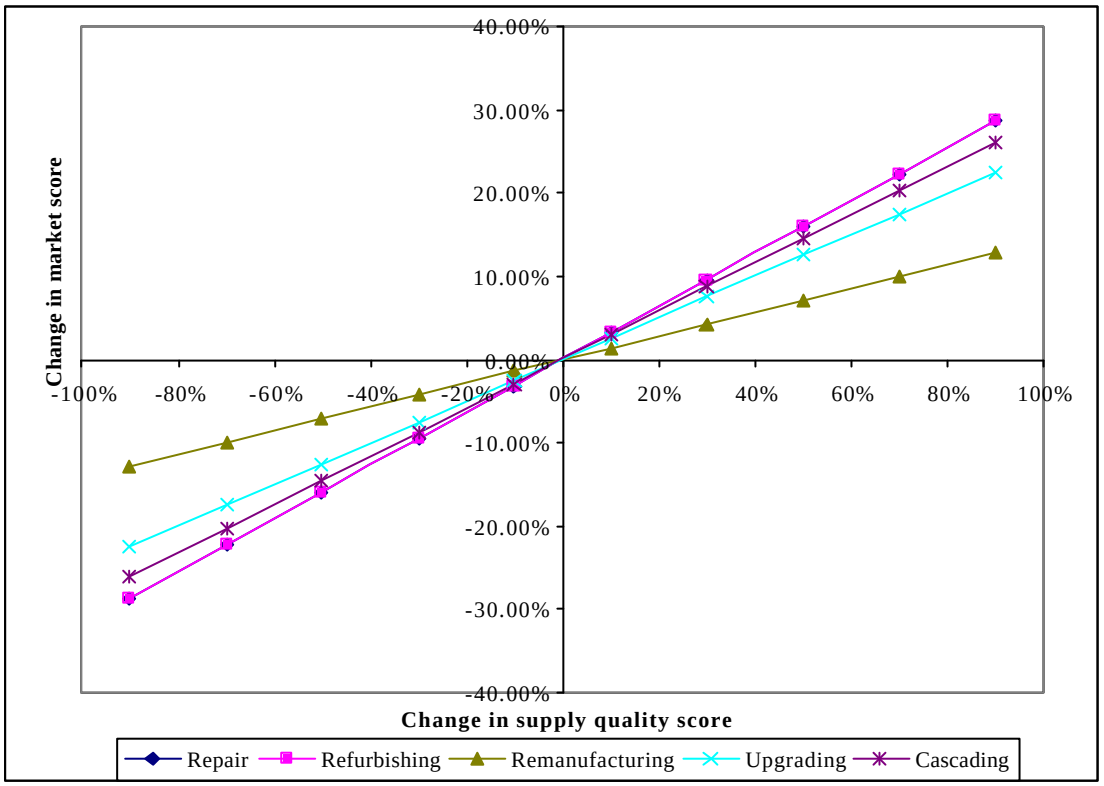


Figure 5.16: Sensitivity of PLETs' market score to changes in supply quality score

5.1.5 Analysis of PLETs' evaluation on time attribute

The results of process time evaluation of PLETs with regard to the shelling machine under the given conditions (see Table 5.10 on page 146) show that only the cascading process satisfied the overall minimum standard on process time. The results also identified cascading as the best PLET. This implies that cascading process has the highest production rate. The sensitivity of PLETs' time scores to changes in time sub-attributes scores (Figures 5.19 –5.22 on pages 146 to 148) shows that changes in operations time has the greatest influence on process time while changes in auxiliary time has the least influence.

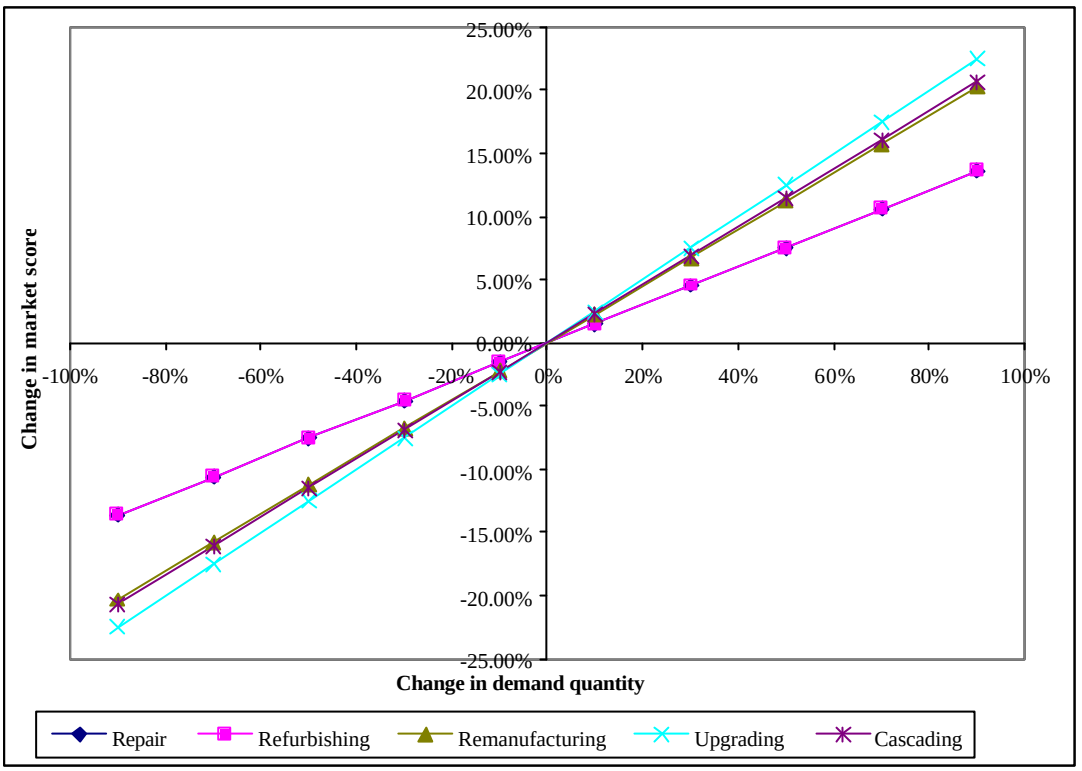


Figure 5.17: Sensitivity of PLETs' market score to changes in demand quantity score

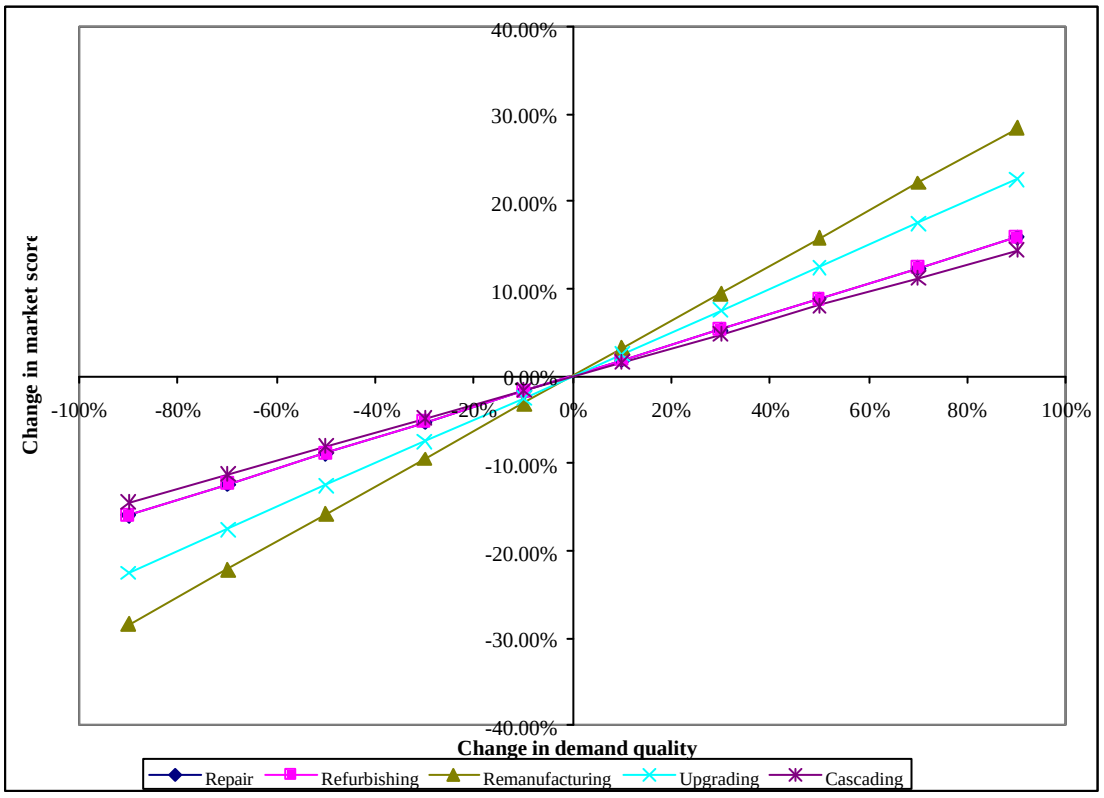


Figure 5.18: Sensitivity of PLETs' market score to change in demand quality

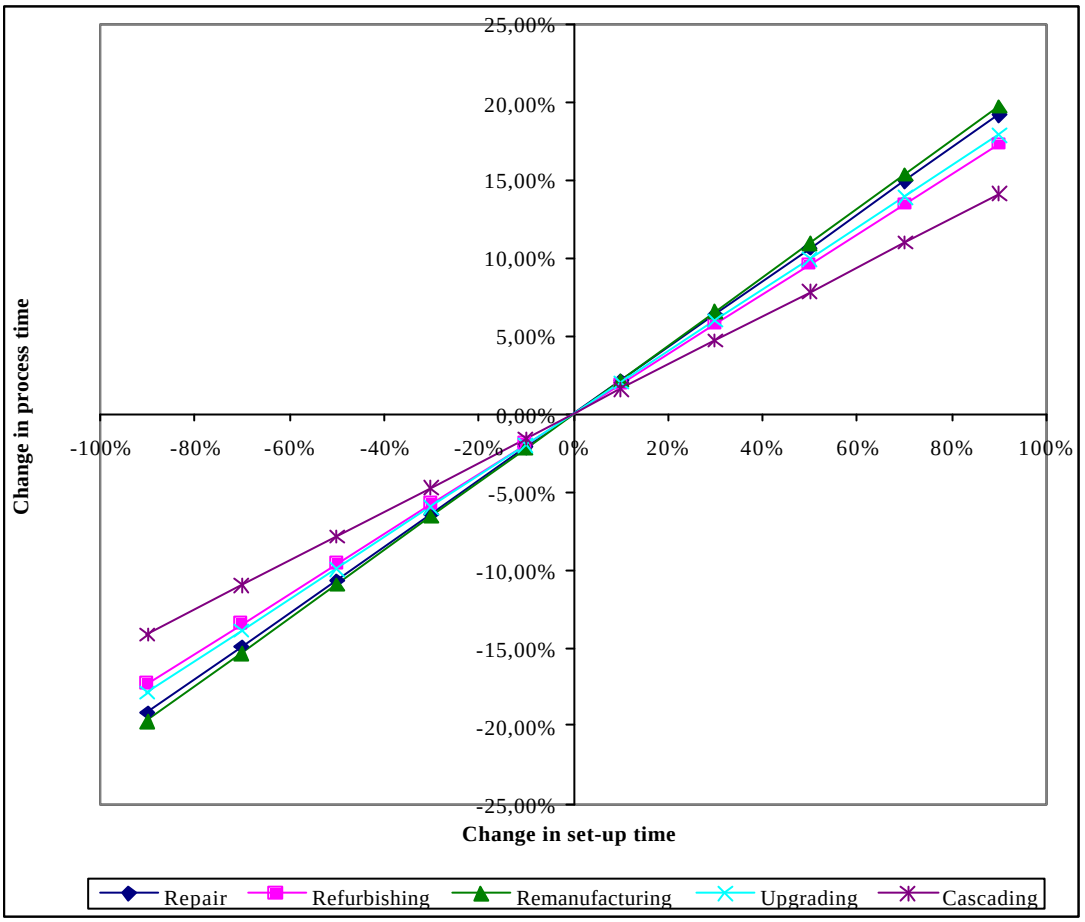


Figure 5.19: Sensitivity of process time to change in set-up time

PLET option	Normalised values				Sum	Time score T_{PLET}
	Set-up time t_{SUT}	Actual operations time t_{AOP}	Auxiliary time t_{AUX}	Delay time t_{DEL}		
Repair	0.250	0.650	0.033	0.240	3.00	0.8099
Refurbishing	0.308	0.933	0.042	0.320	2.20	0.6093
Remanufacturing	0.408	1.083	0.050	0.320	1.90	0.5300
Upgrading	0.334	1.117	0.007	0.224	3.00	0.8183
Cascading	0.217	0.917	0.005	0.240	3.60	1.0000
Minimum standard	0.925	1.725	0.050	0.320	1.40	0.3874

Table 5.10: Comparison of PLETs' normalised time attribute scores with the minimum standard

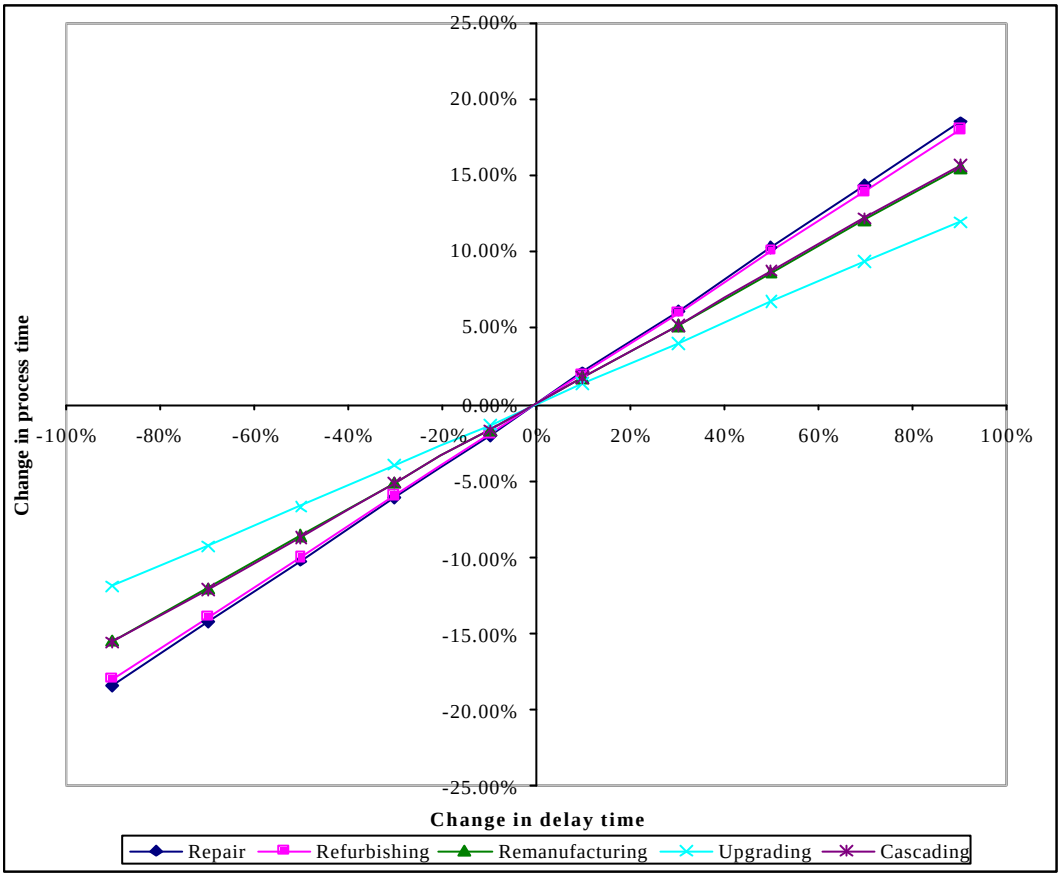


Figure 5.20: Sensitivity of the process time to change in delay time

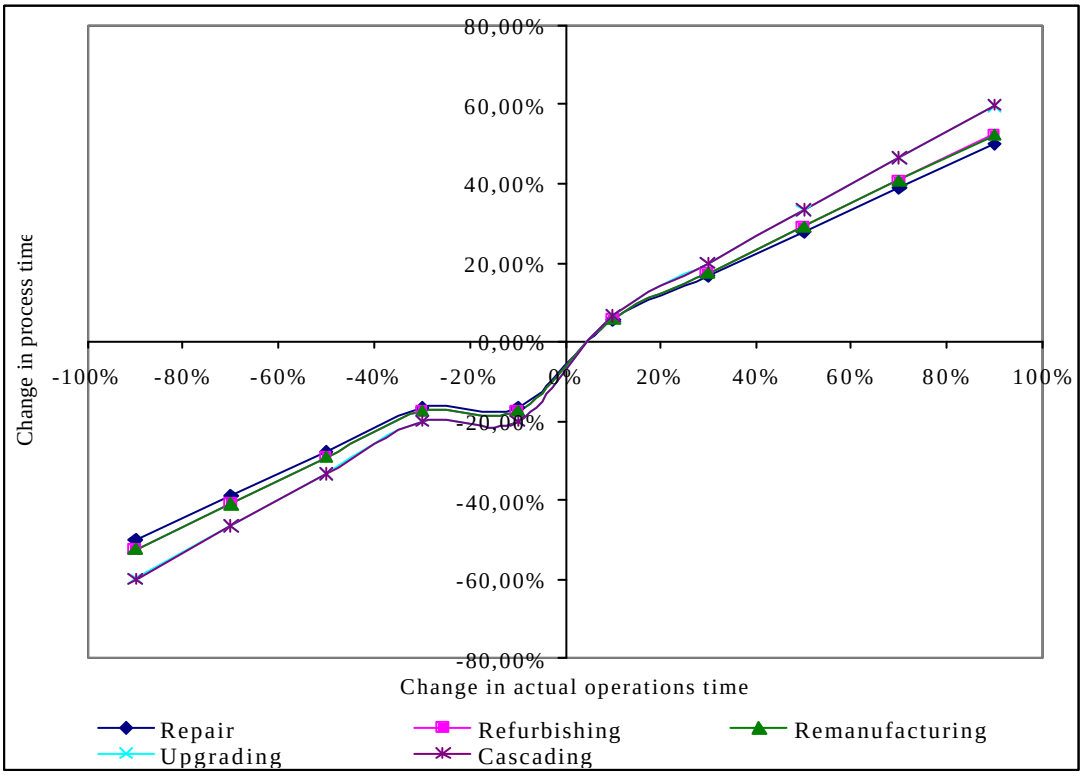


Figure 5.21: Sensitivity of process time to change in actual operations time

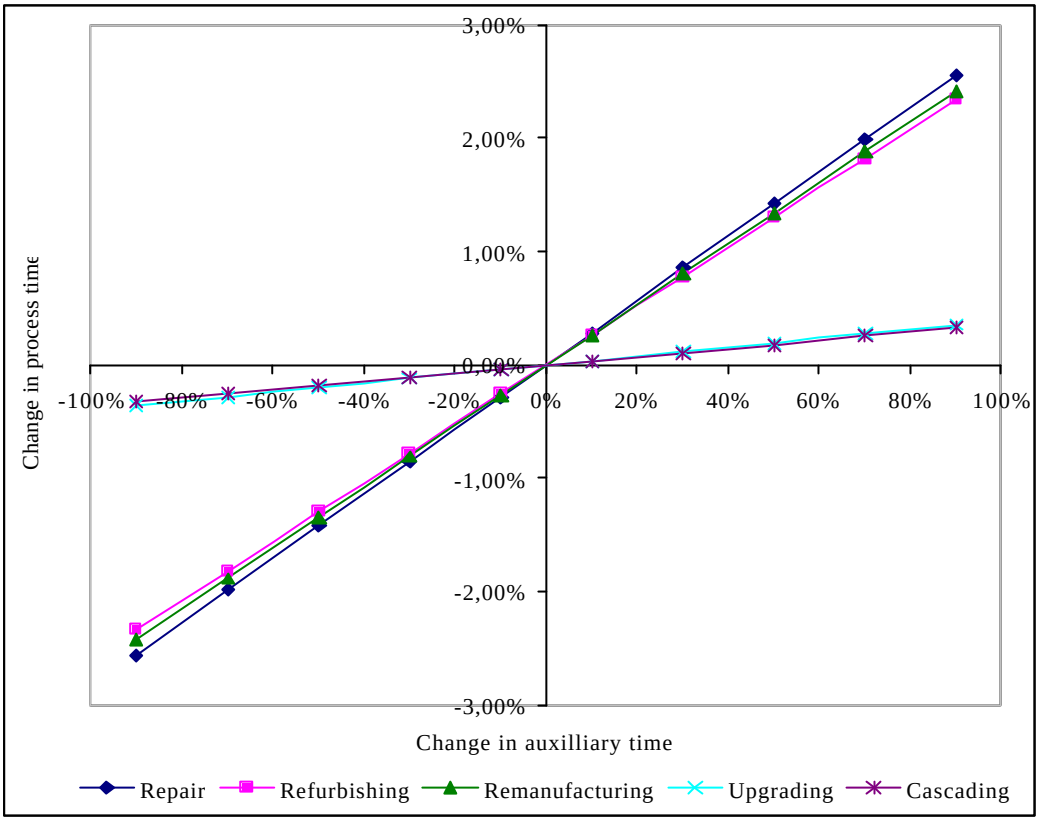


Figure 5.22: Sensitivity of process time to change in auxilliary time

5.1.6 Analysis of PLETs' evaluation on legislative attribute

Table 5.11 shows the legislative conformity of the PLETs. The results show that only repairs process conformed to all the legislative requirements even though cascading has the highest score on the positive aspect (see section 2.1.3 in chapter 3 for details on positive and negative aspects of legislative attribute).

PLET option	L_{MPIS}	L_{MNIS}	L_{PLET}
Repair	0.785	1.000	1.000
Refurbishing	0.446	-1.000	-0.311
Remanufacturing	0.315	-1.000	-0.384
Upgrading	0.369	-1.000	-0.353
Cascading	1.000	-1.000	0.000

Table 5.11: PLETs' legislative conformity scores

[L_{MNIS} Negative Legislative conformity score under mandatory condition
L_{MPIS} Positive Legislative conformity score under mandatory condition
L_{PLET} Legislative conformity score]

The sensitivity of PLETs' legislative scores to changes in legislative sub-attributes scores can be observed in Figures 5.23 and 5.24. Apart from cascading process that shows no change to changes in negative legislative sub-attribute, all others showed linear changes (Figure 5.23). This Figure also shows that refurbishing is the most affected while repair is the least affected. Furthermore, Figure 5.24 (on page 150) shows that changes in positive legislative sub-attributes results in linear changes in PLETs' legislative scores. One can see here that changes in this sub-attribute score also result in infinite change in cascading process score on legislative attribute. Moreover, increase in positive legislative scores leads to increase in repair process score on legislative attribute but decrease in legislative scores of other PLETs and vice versa. From Figures 5.23 and 5.24 it can be observed that refurbishing is the most affected PLET while repair is the least affected. From Figure 5.23 one can see that for every 30% change in negative legislative scores there is between about 0% (for cascading) to about 50% (for refurbishing) change in PLETs' legislative scores while Figure 5.24 shows that for every 30% change in positive legislative scores, PLETs legislative scores changes by between 0% (for cascading), 15-25% (for refurbishing, remanufacturing and upgrading) and 13% (for repairs). From this trends in changes of PLETs' legislative scores due to changes of legislative elements, it can be concluded that negative legislative sub-attribute have overriding influence on PLETs' legislative scores.

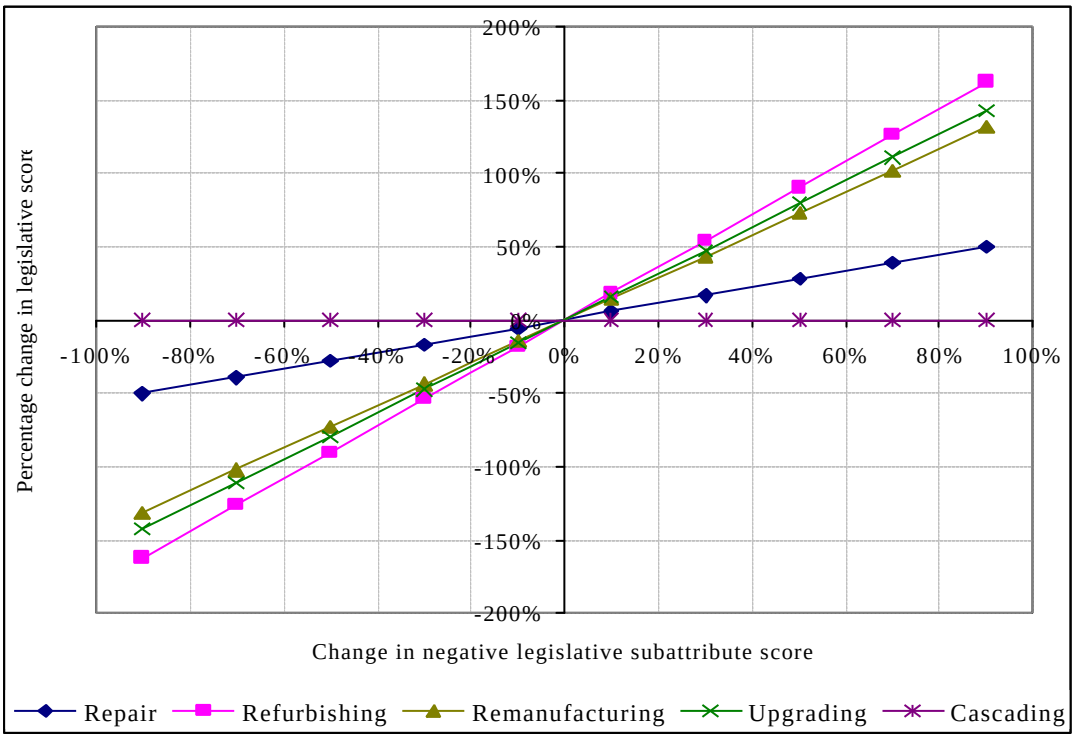


Figure 5.23: Sensitivity of PLETs' legislative scores to changes in negative legislative sub-attribute scores

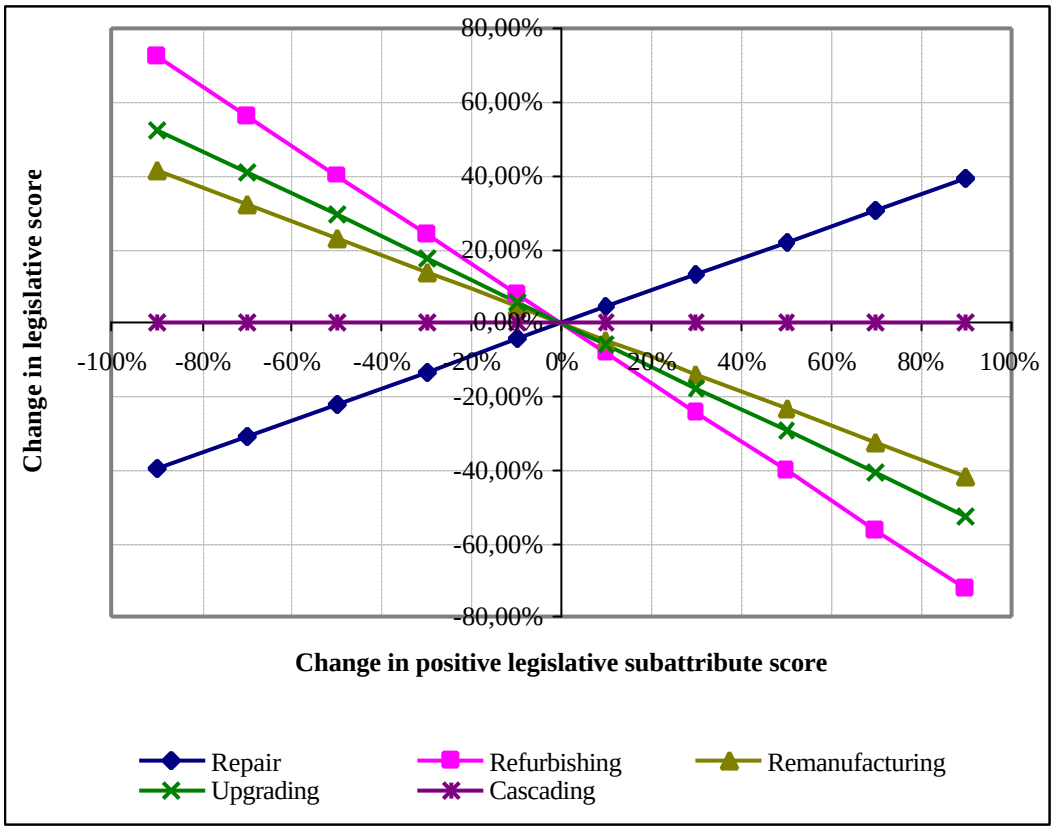


Figure 5.24: Sensitivity analysis of PLETs' legislative scores to changes in positive legislative sub-attribute scores

5.2 Analysis of PLETs' evaluation results on multiple attributes

Assuming PLET selection decisions are to be based on only one of the aforementioned attributes, the highest-ranking PLET that satisfied the required minimum standard in each case would be chosen by the rational decision maker of category 3 (see chapter 3). Simultaneous consideration of the six attributes in PLET selection decision analysis ranks repair process as the best process for the extension of the sheller lifecycle. Tables 5.12 and 5.13 show that repair process is followed by cascading, refurbishing, upgrading and remanufacturing in a descending order of ranking.

PLET option	Cost attribute	Technical attribute	Environmental attribute	Market attribute	Time attribute	Legislative attribute	Overall score O_{PLET}
Repair	0.9952	1.0000	1.0000	0.7071	0.8099	1.0000	5.5123
Refurbishing	0.9546	0.9259	0.7287	0.7071	0.6092	-0.3106	0.0000
Remanufacturing	0.8202	0.7500	0.5583	0.7911	0.5300	-0.3836	0.0000
Upgrading	0.7500	0.6759	0.5640	1.0000	0.8183	-0.3534	0.0000
Cascading	1.0000	1.0000	0.9524	0.7786	1.0000	0.0000	0.0000
S_{MIN}	0.8104	0.5000	0.6620	0.7301	0.3874	0.0000	0.0000

Table 5.12: Comparison of PLETs' normalised scores to various minimum standards

PLET option	C_{PLET}	T_{PLET}	E_{PLET}	M_{PLET}	t_{PLET}	L_{PLET}	**Sum**	O_{PLET}
Repair	1.00	0.97	1.00	0.71	0.81	1.00	5.49	1.00
Refurbishing	0.93	0.79	0.73	0.71	0.61	-0.31	3.46	0.63
Remanufacturing	0.75	0.87	0.56	0.79	0.53	-0.38	3.11	0.57
Upgrading	0.70	0.55	0.56	1.00	0.82	-0.35	3.29	0.60
Cascading	1.00	1.00	0.95	0.78	1.00	0.00	4.73	0.86

Table 5.13: PLETs' scores for the shelling machine on each attribute

[C_{PLET} Normalized cost score
T_{PLET} Normalized technical score
E_{PLET} Normalized environmental score
M_{PLET} Normalized market score
t_{PLET} Normalized time score
L_{PLET} Normalized legislative score
O_{PLET} Overall score (summation)]

5.3 Solution to Sheller Lifecycle Extension Decision Problem

There are three possible solutions to this decision problem, all of which happen to be identical for this case study: Firstly, based on equation 3.8 and the results in Table 5.12 which shows that only repair process satisfied the minimum standards on all the attributes, a satisficing decision maker will choose the repair process alternative. Secondly, on the basis of equation 3.9 and Table 5.13, a benefit maximising decision-maker will select repair as the best process for the extension of the lifecycle of the shelling machine under the various conditions specified because it has the highest overall score (O_{PLET}). Thirdly, using equation 3.10, repair is the preferred solution because it both satisfies all the minimum standards on all attributes and has the highest overall score. These results can also be seen in Figures 5.25 and 5.26 (on page 152). Therefore, repair is the most suitable process for the extension of the shelling machine's lifecycle under the given conditions.

The consideration of the influence of changing importance of cost on the multi-attribute evaluation of PLETs with regard to the shelling machine (Figure 5.27 on page 153) revealed that whatever the change in cost, repair process is the best PLET. Figure 5.27 further shows that repair is the most ranking PLET even when cost is not relevant (i.e. not included in the attributes used) in the multi-attribute analysis. Moreover, the Figure also shows that if cost importance value is increased by 40% the refurbishing process will overtake upgrading process in PLETs' priority listing.

Figure 5.28 (on page 153) shows that the behaviour of PLETs' graphs in relation to changes in importance of technical attribute is similar to the response of PLETs to changes in costs (Figure 5.27). The only exception is in the upgrading process graph in Figure 5.28 which became non-linear from the point at which technical importance increased by 180%. Apart from minor differences in the PLETs' scores shown in Figure 5.29 (on page 154)

from that of Figures 5.27 and 5.28, the PLETs' graphs in this case are also similar to the previous two Figures.

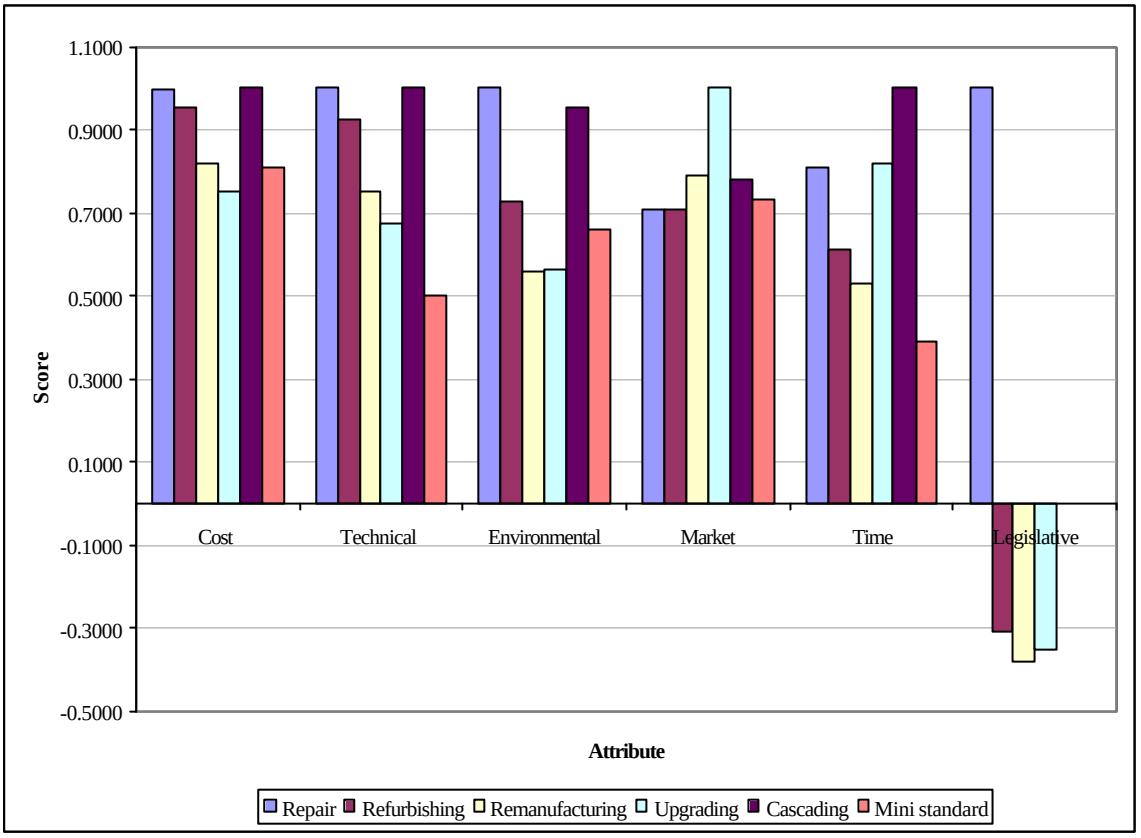


Figure 5.25: Comparisons of PLETs' performances on each of the attributes

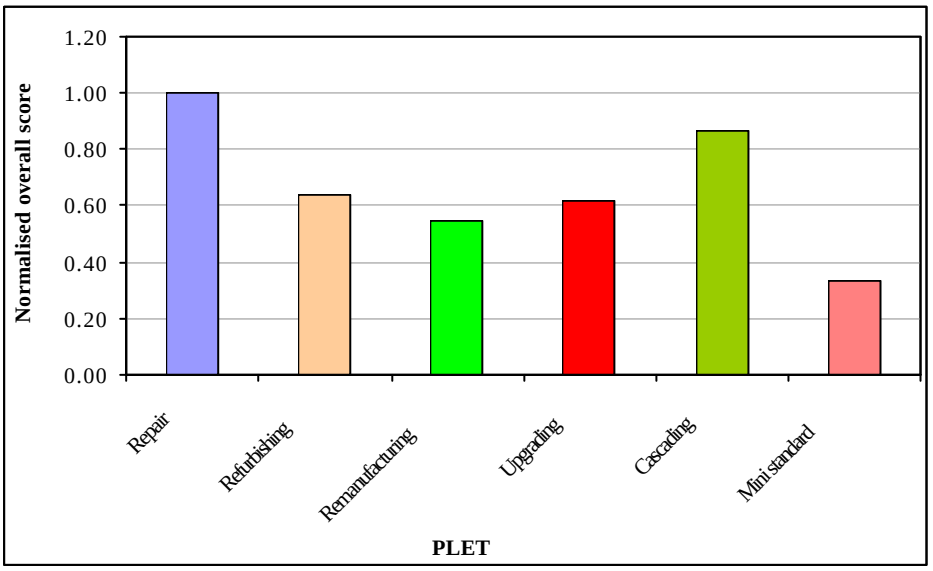


Figure 5.26: PLETs' overall performance on all attributes

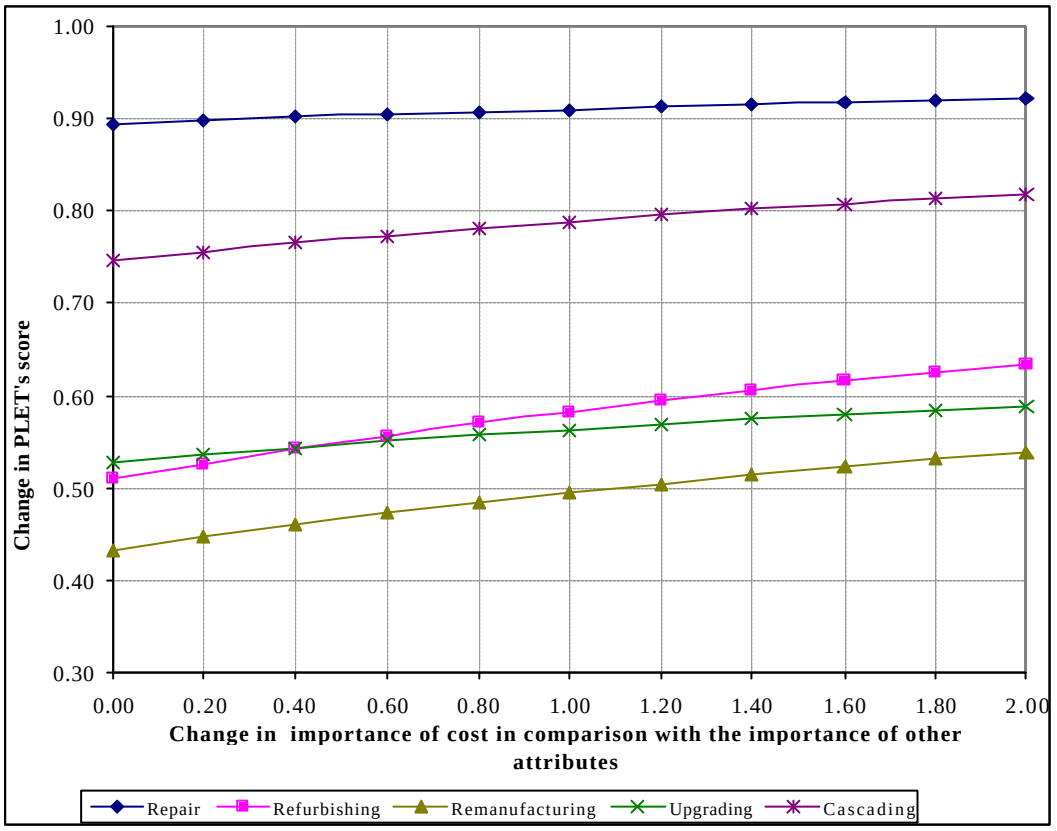


Figure 5.27: Sensitivity of PLETs' overall score to change in importance of cost

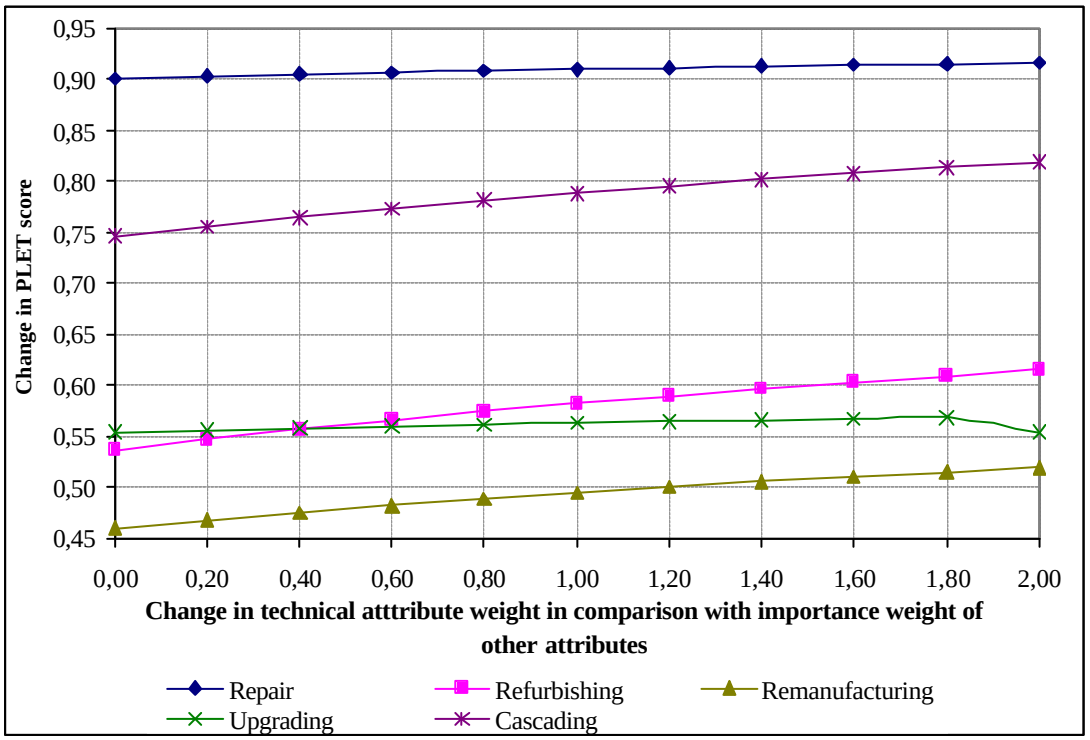


Figure 5.28: Sensitivity of PLETs' score with change in importance of technical attribute

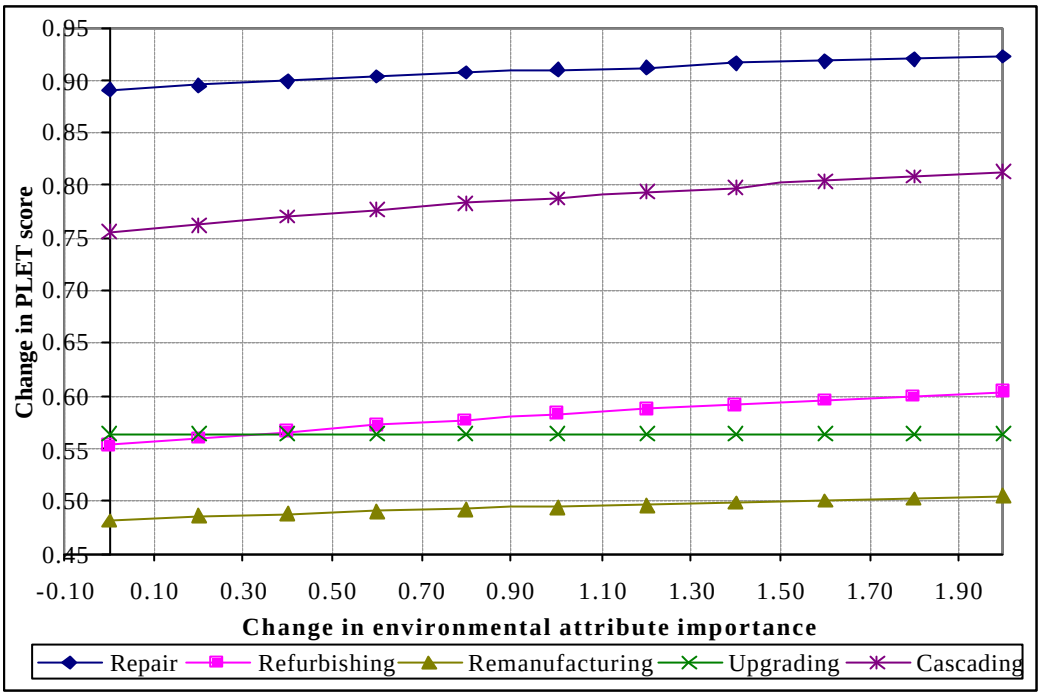


Figure 5.29: Sensitivity of PLETs' score to change in environmental attribute importance

Figure 5.30 shows that increasing change in market attribute importance results in decreasing repair score and increasing scores of refurbishing, remanufacturing and upgrading processes. The changes resulted in the replacement of refurbishing with upgrading process in the priority ranking. However, the overall preference still falls on repair process.

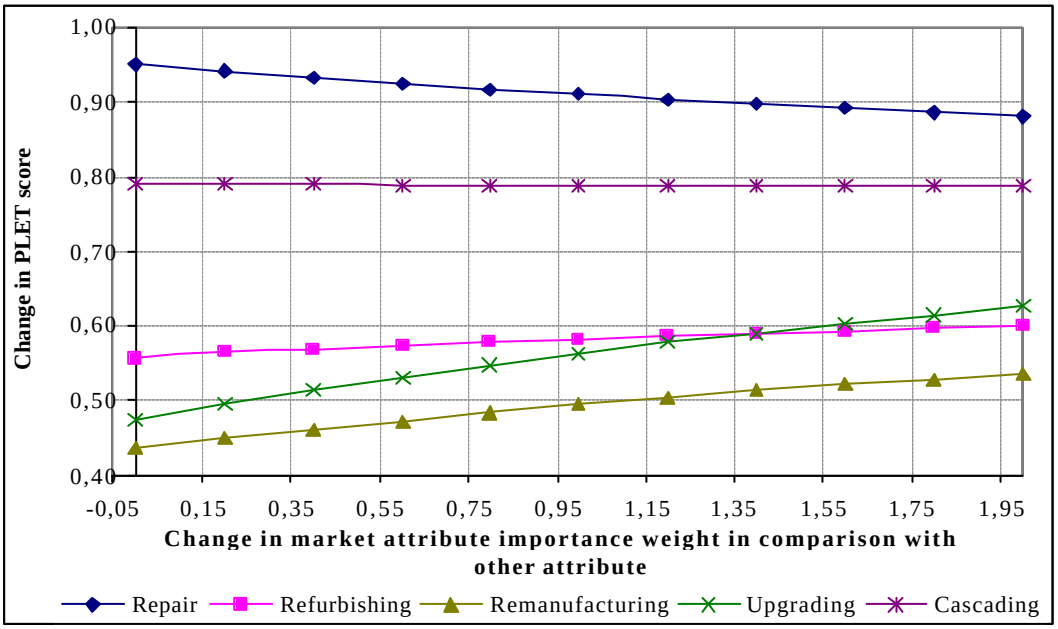


Figure 5.30: Sensitivity of PLETs' score to changes in market attribute importance

Figure 5.31 on the influence of changes in time attribute importance on PLETs' scores shows similar pattern of results to that of Figure 5.31 except the marked impact of time changes on cascading

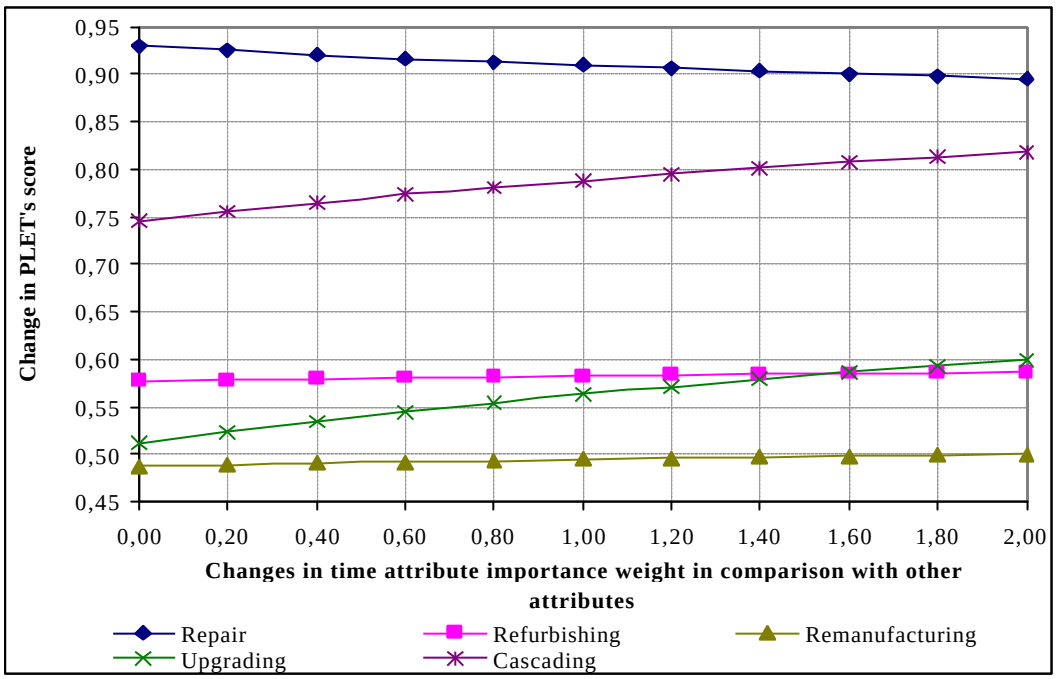


Figure 5.31: Sensitivity of PLETs' score to changes in importance weight of time attributea

Figure 5.31 showed distinctive differences in pattern to the previous five. As increasing changes in legislative importance results in increased repair process score, it results in decreasing scores of all other PLETs.

By comparing the PLETs' graphs in Figures 5.27 –5.32, one can conclude that: only changes in importance of the legislative attribute affect the highest-ranking PLET in the multi-attribute analysis. It can be observed that as the importance of legislative attribute in comparison with other attributes increases from about 28%, repair process takes over from cascading as the highest-ranking PLET. Furthermore one can also see that while increase in legislative importance results in higher repair process performances, other PLETs' performances decline.

Moreover, Tables 5.14 and 5.16 show the results of multi-attribute analysis of product life extension processes with regard to the shelling machine as displayed by the INFORES. While Table 5.14 shows the priority listing of PLETs on each attribute, Table 5.15 shows the priority listing of PLETs with regard to unweighted- and weighted multi-attribute

analysis. Table 5.16 shows the response of PLETS models to parametric questions which are product specific, in this case the product being a multipurpose shelling machine. The general conclusion on this work and recommendations will be found in the next chapter.

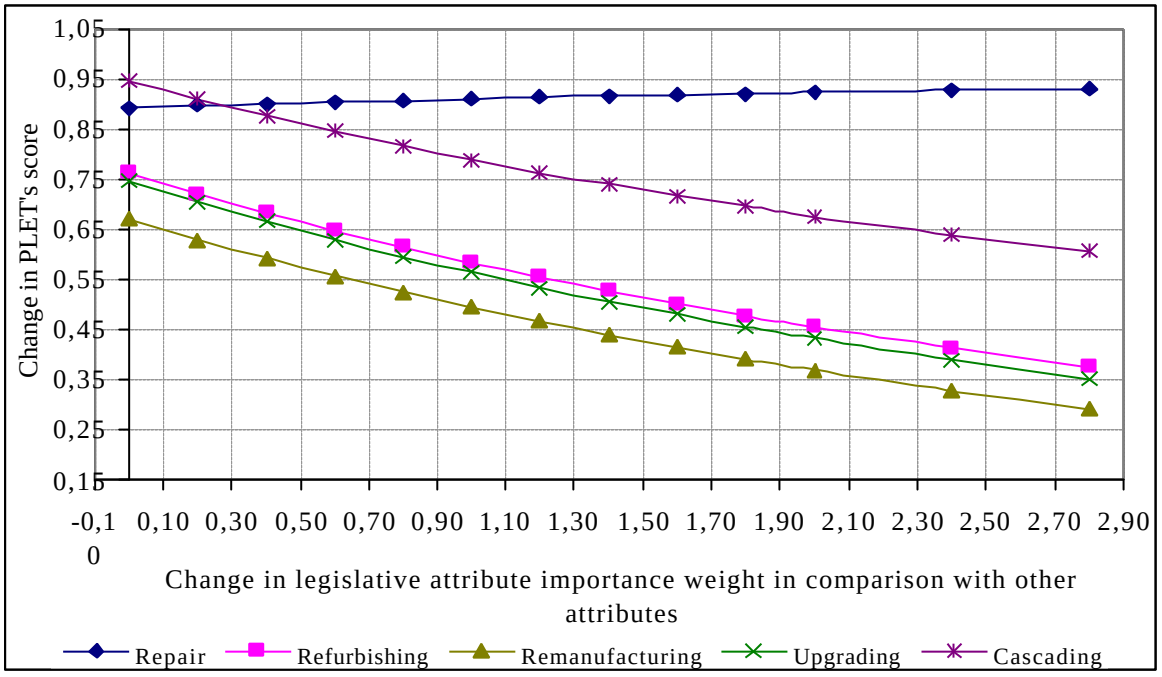


Figure 5.32: Sensitivity of PLETs' score to changes in legislative attribute importance

Priority listing/ranking of product life extension processes that satisfied minimum standard on:

Cost	attribute is	Repair,	Cascading,	Refurbishing,	Remanufacturing	and Upgrading	**processes**
Technical		Repair,	Cascading,	Refurbishing,	Remanufacturing	and Upgrading	
Environmental		Repair,	Cascading,	Refurbishing,	Upgrading	and Remanufacturing	
Market		Upgrading,	Remanufac-turing,	Cascading,			
Time		Cascading,	Upgrading,	Repair,	Refurbishing	and Remanufacturing	
Legislative		Repair					

Table 5.14: Priority listing of product life extension processes that satisfied the minimum standard on each attribute with regard to the shelling machine

The priority listing/ranking of product life extension processes for the sheller on the basis of:

Unweighted multiattribute consideration	Weighted multiattribute consideration and meeting overall minimum standard (Equal weights are used for this specific computation)
1 Repair	1 Repair
2 Cascading	2 Cascading
3 Refurbishing	3 Refurbishing
4 Upgrading	4 Upgrading
5 Remanufacturing	5 Remanufacturing
The preferred/recommended PLET is:	Repair process

Table 5.15: The priority listing of product life extension processes on multi-attribute analysis basis

1 Can the product's lifecycle be extended? (Product life extendibility)	*Yes*				
2 Is the reworked product marketable? (Reworked product marketability)	*Yes*				
3 Are the available facilities suitable for extending the product lifecycle? (Facilities suitability for PLE)	*Yes*				
4 Will the extension of the product lifecycle conform to legislative requirements? (Legislative conformability of extending the product life)	*Yes*				
	Repair	Refurbish-ing	Remanu-facturing	Upgrad-ing	Cascad-ing
5 What is the time required by each PLET? (Process time in minutes)	1.17	1.60	1.86	1.68	1.38
6 What is the cost of reworking the product by using each of the PLET? (Process cost in DM)	227.38	236.88	279.48	302.64	224.43

Table 5.16: PLETS Models response to the product life extension questions

6 Conclusion and Future Research

From the aforementioned results of the decision analysis discussed in chapters 4 and 5, one can see both the application and the comprehensiveness of the decision model. The results also show how the trade-offs in using a specific product life extension process changes with the attribute considered. From the tables and graphs in chapter 5 one can also observe how changes in sub-attribute values affect the results seen at the attribute level. The behaviour of the model revealed that changes in importance of the decision attributes resulted in changes in the recommended PLET at some specific points. The graphs of effects of changes in values and importance are also generally linear apart from some few exceptions. The overall result on this case study showed that repair is the best process. Comparing this result with what is practically applicable for this decision scenario, it showed that the model is an adequate decision making aid for real world applications.

- **Contributions of research**

The main contribution of this research is the development of a systematic methodology for product life extension process selection and a computer implementation prototype to facilitate the application of the proposed methodology. Another contribution made by this work is setting minimum standard on each attribute used for PLET evaluation. The case study of a multipurpose sheller also illustrated the use of the method and tested the accompanying demonstrative decision support tool. Furthermore, the hybridisation of a number of decision making methods that resulted in this decision analysis model is also a contribution. The application of the hybridised decision making methodology is another contribution, as it is the first time of its being applied in resource use intensification and recovery domain. Similarly, the inclusion and simultaneous consideration of such factors like technical-, market-, and legislative attributes in addition to the traditionally used environmental and cost factors for the evaluation of the product end-of-life options is unprecedented in this area of research. This credible comprehensive management tool will be found useful in product lifecycle extension decision making domain. Manufacturing firms and marketers that are mandated under Part 3, art 22 of the German Waste avoidance, recycling and disposal act of 1994 to take back their product at the end of their service life will find the multidimensional analytic frameworks provided by this work very helpful in identifying the best course of action to take in meeting their legislative obligations without jeopardising their corporate interests. By focusing on the utilisation

and end-of-life stage of product lifecycle management, this work has made contribution in the facilitation of the fulfilment of some aspects of product responsibility contained in Part three, arts 22, 23 and 24 of German waste avoidance, recycling and disposal act of 1994. The use of this algorithm will particularly enable firms to analyse the possibilities for return, reuse and recycling of their product (Part3 Art 22, para 2, section 4) as well as assist them in assessing the economic consequences of various options that are open to them.

- **Critique**

As good as the model is, it has some drawbacks. The major drawback is the size of the model, with the consequent requirement for large number of data which may either not be available or require a long time to obtain. However, the build-up of the model in modules as well as the in-built subjective assessment technique enables the evaluation process in the absence of some data. By this action, the aforementioned demerit has been eliminated.

Furthermore, the interdependent nature of some attributes makes a PLET performance on one attribute to be affected by their performance in another attribute. This violates the requirement for independence of attributes in linear SAW. Such interdependency of attributes necessitates the use of non-linear SAW. However, Hwang and Yoon (1981) reported that the difference in the output of linear- and non-linear SAW is so negligible that sacrificing the little improvement in using non-linear SAW pays than engaging in computation rigour involved in non-linear SAW.

- **Future Research**

Extension of the application of the work to other decision maker categories

Although this algorithm can be used by various categories of decision-makers interested in product life extension, however, the model was built with focus on firms having product take-back obligation in mind. The decision makers in that category are limited to manufacturers and distributors/marketers (part 3, art 24, para. 1). Thus, future work should aim at extending the application of this algorithm to other interest groups such as product users, and renovators/ recyclers.

Investigation of the applicability of other decision making methodologies for PLETS

This decision analysis model is a composite decision making method consisting of modified simple additive weighting method, conjunctive method and mixed value

functions. It is believed that other methods such as TOPSIS, AHP, LINMAP and so on can also be used. Comparative analysis of these methods' suitability for PLETS is considered necessary in future research.

Extension of the investigation to different product groups

The decision model is built with investment (mechanical) products in mind. However, it can also be used for electromechanical products. Future research can be directed at extending the application of the model to consumable products, chemical products and others. Future research may also be directed at comparative evaluation of the behaviour of different product groups.

This work has thus demonstrated the potentials in resource use intensification and asset recovery. It also enunciated the decision problem in this domain and provided a credible decision analysis model for meeting such management decision making needs.

Summary

The increase in environmental campaign has opened up opportunities for intensive resource utilisation, recovery and reuse. However, before these opportunities can be wisely- and fully harnessed, the assets to be reused have to be given some treatments. It has been discovered that the opportunities abounding in resource use intensification, recovery and reuse has some correlation with the treatments that could be given. In view of the availability of various opportunities and their links with various treatments that are to be given in order to achieve the goals of maximising the benefits inherent in resource use intensification and reuse, a problem of choosing between the various treatments that will yield a specific goal arise. Before a choice can sensibly be made, a number of factors have to be considered and be used to evaluate the various options with the aim of selecting the best option under the given circumstances. Despite all research efforts thus far being put into resource recovery and reuse, none has been found to consider the decision-making aspect of resource use intensification and recovery in a comprehensive manner. Most of the research works focuses on the development of some aspect of product life extension techniques in the areas like product take-back logistics, and fasteners. Others focus on product design that facilitates resource recovery and reuse.

The absence of a comprehensive decision making framework in the area of resource use intensification, recovery and reuse served as a research gap that this work set out to fill. This work developed a product-life-extension-process selection methodology, and a demonstrative computer implementation of the methodology. The application of the methodology is illustrated with a case study. The product life extension methodology focused on the selection of processes that can be applied at the utilisation and retirement stages of product lifecycle. Such identified processes that enhance the asset use intensification and reusability of a product at the aforementioned stages are repair and maintenance, refurbishing, remanufacturing, upgrading and cascading. A number of factors considered essential for consideration in product life extension process selection are grouped into six attributes, namely: cost, technical, environmental, market, time and legislative attributes. Each of them is made up of sub-attributes, and sub-sub-attributes. The discrete nature of process options and largeness in number of factors to be considered necessitate the use of a multiple attribute decision-making method. The developed decision model is essentially a hybridisation of two decision-making methods: conjunctive method and simple additive weighting method. The conjunctive method screens out the processes that fail to meet set standard at the attribute level and at the overall level. The simple additive weighting method measures the tradeoffs between the alternatives that satisfied

the set standards. The correlations at foundational stage of each attribute is made up of distributive value functions while the upper levels of PLETS attributes hierarchical structure are simple additive correlations. The values and scores obtained at various levels of evaluations are normalised for uniformity of scaling. Sensitivity analysis was also integrated into the methodology in order to analyse the sensitivity of the results obtained from the methodology to changes in values and scores of some parameters used.

The demonstrative computer implementation prototype is built by using MS Excel programme and it is divided into three modules: INFOCOL, INFOPRO and INFORES. INFOCOL is information collection module that serves as user-computer interaction interface of the methodology. This module itself consists of six sheets of questions which user have to answer. Each sheet of questions is for each attribute. INFOPRO is the module that processes the information entered at the INFOCOL. It consists of mathematical correlation developed to evaluate the sub-sub-attributes, sub-attributes and attributes with respect to the particular process option. INFORES is the module that displays the results of information processed at INFOPRO in linguistic, numerical, chart and graphical forms.

The results of the case study used to illustrate and to validate the proposed methodology, and its computer implementation prototype show that repair is the best process for the extension of the lifecycle of the shelling machine when all the attributes are of equal importance. The results also showed that change in importance of one or more attributes' score brings about significant changes in PLETs' scores and often result to changes in the ranking of decision alternatives. The sensitivity analyses of the impact of changes in the sub-attribute values on the attribute score also showed that many of the sub-attribute changes affects the attribute score while little changes occur as a result of changes in some sub-attributes.

Entering some data or changing some entered data in the INFOCOL bring about results or changes in results: in numerical, linguistic and graphical forms. The response of the computer implementation of the methodology showed that the goal of the research has been reached. The similarity in the recommended process by this methodology with what obtains in practice with regard to this product under the given condition also proved the suitability of this methodology.

This work, by establishing parameters needed for the evaluation of product life extension processes; by developing a suitable correlations for decision making in product lifecycle extension domain; as well as by developing framework for setting minimum standard on major decision making parameters and demonstrating its applications, will be found useful by resource- and waste management decision makers.

Zusammenfassung

Die intensive Diskussion um die Erhaltung der Umwelt hat neue Möglichkeiten für die verstärkte Nutzung, Rückgewinnung und Wiederverwendung von Ressourcen eröffnet. Bevor diese Möglichkeiten jedoch klug und in vollem Umfang genutzt werden können, müssen die Produkte, die wiederverwendet werden sollen, eine geignete Aufbereitung erfahren. Es zeigte sich, daß die reichlich vorhandenen Möglichkeiten in Bezug auf intensive Nutzung, Rückgewinnung und Wiederverwendung von Ressourcen mit den potentiellen Aufbereitungsmethoden in einer Wechselbeziehung stehen. Angesichts des Vorhandenseins verschiedener Möglichkeiten und ihrer Verbindung zu den unterschiedlichen Aufbereitungsmethoden, steht man vor der Wahl mit derm Ziel der Nutzenmaximierung. Bevor eine vernünftige beziehungsweise beste Wahl getroffen werden kann, muß eine Reihe von Faktoren betrachtet und genutzt werden, um die verschiedenen Optionen zu bewerten. Trotz aller bisherigen Anstrengungen, auf dem Gebiet der Forschung zur Rückgewinnung und Wiederverwendung von Ressourcen wurde bis jetzt keine allgemeingültige Methode der Entscheidungsfindung bei der verstärkten Verwendung und Rückgewinnung von Ressourcen entwickelt. Die meisten Forschungsarbeiten konzentrieren sich auf die Entwicklung einzelner Aspekte zur Verlängerung der Lebensdauer von Produkten auf Gebieten wie Produktrücknahmelogistik und entsprechende Verantwortlichkeiten. Andere Arbeiten konzentrieren sich auf Produktausführungen, die die Rückgewinnung und Wiederverwendung von Ressourcen erleichtern.

Das Nichtvorhandensein eines umfassenden Entscheidungsrahmens auf dem Gebiet der verstärkten Nutzung, Rückgewinnung und Wiederverwendung von Ressourcen erwies sich als eine Forschungslücke, die mit dieser Arbeit gefüllt werden soll. Mit der vorliegenden Arbeit wurde eine Methode zur Auswahl eines Prozesses, der die Verlängerung der Lebensdauer eines Produkts zum Ziel hat, sowie eine anschauliche computergestützte Umsetzung der Methodik entwickelt. Die Anwendung der Methodik wird an Hand einer Fallstudie veranschaulicht. Die Methode zur Verlängerung der Lebensdauer von Produkten konzentrierte sich auf die Auswahl von Prozessen, die im Lebenszyklus eines Produkts sowohl in der Gebrauchs- als auch in der Außerbetriebnahmephase relevant sind. Solche Prozesse, die während den zuvor genannten Phasen den Gebrauch von Gütern intensivieren und die Wiederverwendbarkeit von Produkten ermöglichen, sind Reparatur und Wartung, Sanierung, Wiederherstellung, Verbesserung und kaskadenartige Erweiterung. Dieser Faktoren, werden in sechs Attributsklassen eingruppiert, und zwar: Kosten, Technologie, Umwelt, Markt, Zeit und gesetzgebende Merkmale. Jede dieser Klassen besteht aus

Unterklassen und Sub-Unterklassen. Die Unbeständigkeit der Prozeßoptionen und die große Anzahl der zu betrachtenden Faktoren erfordern die Anwendung einer rechnergestützte Methode der Entscheidungsfindung, die viele Attributsklassen abdeckt. Das entwickelte Entscheidungmodell ist im wesentlichen eine Kombination aus zwei Methoden der Entscheidungsfindung: die „Conjunctive“ Methode und die „Simple Additive Weighting“ Methode. Die „Conjunctive“ Methode selektiert die Prozesse, die den für das Niveau der Attributsklasse und für das gesamte Niveau festgesetzten Standard erreichen. Die „Simple Additive Weighting“ Methode bewerte die Kompromisse, die zwischen den Alternativen gemacht werden müssen, um die festgelegten Standards zu erreichen. Die Wechselbeziehungen auf der Grundstufe einer jeden Attributklasse bestehen aus distributiven Wertfunktionen, während die oberen Stufen der Hierarchiestruktur der PLETS-Attributsklasse „Simple Additive Weighting“ Wechselbeziehungen darstellen. Die Werte und Ergebnisse, die man auf verschiedenen Bewertungsniveaus erhält, werden zur Vereinheitlichung der Skalierung normiert. Die Sensitivitätsanalyse wurde ebenfalls in die Methodik einbezogen, um die Anfälligkeit der im Rahmen der Methodik gewonnenen Ergebnisse gegenüber Wertveränderungen einzelner Parameter zu analysieren.

Der zur Veranschaulichung dienende, computergestützte Prototyp wird unter Verwendung des MS- Excel-Programms aufgebaut und in drei Module unterteilt: INFOCOL, INFOPRO und INFORES. INFOCOL ist ein Informationserfassungsmodul, das als Schnittstelle der Wechselwirkung zwischen dem Anwendercomputer und der Methodik dient. Dieses Modul selbst besteht aus sechs Seiten Fragen, die der Anwender beantworten muß. Jede Seite mit den entsprechenden Fragen bezieht sich auf eine Attributsklasse. INFOPRO ist das Modul, das die Informationen verarbeitet, die bei INFOCOL eingegeben werden. Es besteht aus der mathematischen Wechselbeziehung, die entwickelt wurde, um die die Attribute umfassenden Sub-Unterklassen, Unterklassen und Klassen hinsichtlich der besonderen Verfahrensoption zu bewerten. INFORES ist das Modul, das die Ergebnisse der in INFOPRO verarbeiteten Informationen linguistisch, numerisch, als Chart und in graphischer Form anzeigt.

Die Ergebnisse der dargestelten Fallstudie wurden verwendet, um die vorgeschlagene Methodik zu veranschaulichen und zu bestätigen, und der computergestützte Prototyp zeigt, daß die Reparatur der beste Weg ist, um die Lebensdauer der „Shelling“ Maschine zu verlängern, wenn alle Attribute von gleicher Wichtigkeit sind. Die Ergebnisse zeigten auch, dass Veränderungen bezüglich der Wichtigkeit eines oder mehrerer Attribute bedeutsame Veränderungen bei den PLETS-Ergebnissen hervorrufen, und damit auch oft zu Veränderungen in Bezug auf die Einordnung von Entscheidungsalternativen führen.

Die Empfindlichkeitsanalysen zur Untersuchung der Auswirkung von Veränderungen in den Werten der Unter-Attributsklasse auf das Attributsergebnis haben auch gezeigt, daß viele Veränderungen auf der Ebene der Unter-Attributsklassen Einfluß auf das Attributsergebnis haben, während kleine Veränderungen als Ergebnis von Veränderungen in einer Unter-Attributsklasse auftreten.

Die Eingabe von Daten in das INFOCOL-Modul oder die Veränderung von eingegebenen Daten bringen Ergebnisse hervor oder verändern sie, und zwar in numerischer, linguistischer und graphischer Form. Die welche auf die computergestützte Methodik hat gezeigt, daß das Ziel der Forschung erreicht worden ist. Die Ähnlichkeit der Methodik, die in dem empfohlenen Verfahren angewandt wurde, mit dem, was im Hinblick auf dieses Produkt unter den gegebenen Bedingungen erreicht wird, hat die Eignung dieser Methodik nachgewiesen.

Durch Aufstellung von Parametern, die für die Bewertung von Verfahren zur Verlängerung der Lebensdauer von Produkten benötigt werden, will die Entscheidungstrager von Resourcen-und Versorgung Management dieser Arbeit nutzlich finden, und zwar durch die Aufstellung von Rahmen für die Festlegung von Mindeststandards für wichtige, der Entscheidungsfindung dienende Parameter und durch Veranschaulichung der entsprechenden Anwendungen.

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Appendices: More details on the data used for the Case Study

This section consists of seven sub-sections, namely: the selling parameters and six sub-modules of the INFOCOL containing the information used for the PLETs' evaluation.

Appendix A: The shelling machine parameters

Table A1 shows the component parts, the materials content and the quantity of each material contained in each parts of a new shelling machine. Table A2 shows the estimated percentage materials reckoned unsuitable for achieving a specific quality attributable to each PLET for the shelling machine. From these estimates, the quantity of each materials reusable per unit sheller is calculated and also shown in Table A2.

Part	Average unit weight of the part	Quantity of the parts required per product	Material content in Kg				**Total**	Grease
			Galvanized steel	Mild steel	Carbon steel	Rubber		
New shelling machine							***70.746***	
. Housing	31.800	1	31.800					
. Connectors	1.200	2		2.400				
. Pulley	1.250	3			3.750			
. Bushing	0.030	4		0.120				
. Bearing	0.120	4			0.480			
. Shaft	7.500	2		15				
. Concave	1.200	1	1.200					
. Sieve	4.000	3	12.000					
. Wire rope	0.250	2		0.500				
. Driving belts	0.050	2				0.100		
. Shutter	0.120	1	0.120					
. Shutter guide	0.008	2	0.016					
. Cylinder plates	0.850	2	1.700					
. Rasp bars	0.015	8	0.120					
. Concave adjuster/holder	0.180	4	0.720					
. Fastener	0.015	48	0.720					
			48.396	***18.020***	***4.23***	***0.100***		
Lubricants		0.080						**0.080**

Table A1: Component parts of a shelling machine, their average weights and material content of the parts

PLET	Issue considered	Galvanised steel	Mild steel	Carbon steel	Rubber	Total (Kg)
Repair	Percentage of product material unfit for repair process due to rust, wears and tears	5%	10%	1%	1%	
	Material type lost to rust, wears and tears per product (Kg)	2.4198	1.802	0.0423	0.001	4.2651
	Total reclaimable materials per product (Kg)					**66.481**
Refurbishing	Percentage of product material unfit for refurbishing process due to rust, wears and tears	7%	15%	1%	2%	
	Material type lost to rust, wears and tears per product (Kg)	3.38772	2.703	0.0423	0.002	6.13502
	Total reclaimable materials per product (Kg)					**64.611**
Remanufacturing	Percentage of product material unfit for remanufacturing process due to rust, wears and tears	10%	20%	5%	100%	
	Material type lost to rust, wears and tears per product (Kg)	4.8396	3.604	0.2115	0.1	8.7551
	Total reclaimable materials per product (Kg)					**61.991**
Upgrading	Percentage of product material unfit for upgrading process due to rust, wears and tears	10%	100%	5%	100%	
	Material type lost to rust, wears and tears per product (Kg)	4.8396	18.02	0.2115	0.1	23.1711
	Total reclaimable materials per product (Kg)					**47.575**
Cascading	Percentage of product material unfit for cascading process due to rust, wears and tears	5%	5%	1%	1%	
	Material type lost to rust, wears and tears per product (Kg)	2.4198	0.901	0.0423	0.001	3.3641
	Total reclaimable materials per product (Kg)					**67.382**
Estimated percentage of materials lost to rust/corrosion alone			1%	0.70746		

Table A2: Material content of a taken-back shelling machine

Table A3 shows the estimated part requirements by each PLET on the basis of the percentage parts of the taken back shellers that are unsuitable for the specific quality of rework associated with the PLET. From these estimate, quantity of reusable materials and wastes resulting from the use of a particular PLET for reworking the retrieved shelling machines are calculated.

PLET option	Estimated parts requirements	Measure-ments used for the part	Estimated percentage of the parts that are unreusable for the PLET	Quantity of the part required to rework a unit product by the PLET	Total quantity of the part required per period	Material content in Kg										Reusable- and waste contents expected from the PLET		
						Lubricants		Galvanized steel		Mild steel		Carbon steel		Rubber		**Total** (Kg)	Reusables		Wastes
						Unit weight of material type	Total weight of the material type used per period	Weight of material type per unit product/part	Total weight of the material type used/ spared per period	Unit weight of material type	Total weight of the material type used per period	Unit weight of material type	Total weight of the material type used per period	Unit weight of material type	Total weight of the material type used per period		Average percentage of reusable material	Reused materials or parts	Waste material (Kg)
Repair and maintenance process	Materials (taken-back product per period)	Number			250			45.9762	11494.05	16.218	4054.5	4.1877	1046.925	0.099	24.75	16620.23	94%	15,618.23	1002.0
	Fasteners	Number	5%	2	600					0.015	9					9		11400	9.0
	Bearings	Number	2%	0	20							0.12	2.4			2.4		980	2.4
	Grease	Litres	100%	0	20	0.08	1.6												
	Bushings	Number	1%	0	10					0.03	0.3					0.3		990	0.3
	Belts	Number	1%	0	5									0.05	0.25	0.25		495	0.3
							1.6		***0***		***9.3***		***2.4***		***0.25***	***11.95***			*12.0*
Refurbishing process	Materials (taken-back product)	Number			250			45.00828	11252.07	15.317	3829.25	4.1877	1046.925	0.098	24.5	16152.75	91%	14,752.00	1400.7
	Fasteners	Number	5%	2	600					0.015	9					9		11400	9.0
	Bearings	Number	5%	0	50							0.12	6			6		950	6.0
	Grease	Litres	100%	0.08	20	0.08	20									0			0.0
	Bushings	Number	20%	1	200					0.03	6					6		800	6.0
	Belts	Number	5%	0	25									0.05	1.25	1.25		475	1.3
							20		***0***		***15***		***6***		***1.25***	**22.25**			*22.3*
Remanufac-turing process	Materials (taken-back product)	Number			250			43.5564	10889.1	14.416	3604	4.0185	1004.625	0	0	15497.73	88%	13,579.82	1917.9
	Fasteners	Number	5%	2	600					0.015	9					9		11400	9.0
	Bearings	Number	25%	1	250							0.12	30			30		750	30.0
	Grease	Litres	100%	0.08	20	0.08	20									0			0.0
	Bushings	Number	90%	4	900					0.12	108					108		100	108.0
	Belts	Number	50%	1	250									0.05	12.5	12.5		250	12.5
	Pulleys	Number	2%	0	15							1.75	26.25			26.25		735	26.3
	Concave	Number	5%	0	12.5			1.2	15							15		237.5	15.0
	Shutter	Number	1%	0	2.5			0.12	0.3							0.3		247.5	0.3
	Shutter guide	Number	1%	0	5			0.008	0.04							0.04		495	0.0
	Cylinder plates	Number	60%	1	300			0.85	255							255		200	255.0
	Shaft	Number	3%	0	15							7.5	112.5			112.5		485	112.5
	Concave adjuster/holder	Number	5%	0	50			0.18	9							9		950	9.0
	Wire rope	Number	20%	0	100					0.25	25					25		400	25.0
	Sieve	Number	1%	0	7.5			4	30							30		742.5	30.0
							20		***309.34***		***142***		***168.75***		***12.5***	***632.59***			*632.6*
Upgrading process	Materials (taken-back product)	Number			250			43.5564	10889.1	0	0	4.0185	1004.625	0	0	11893.73	67%	7,998.23	3895.5
	Housing	Number	100%		0														
	Fasteners	Number	5%	2	600					0.015	9					9		11400	9.0
	Bearings	Number	25%	1	250							0.12	30			30		750	30.0
	Grease	Litres	100%	0.08	20	0.08	20									0			0.0
	Bushings	Number	90%	4	900					0.03	27					27		100	27.0
	Belts	Number	50%	1	250									0.05	12.5	12.5		250	12.5
	Concave	Number	2%	0	5							1.75	8.75			8.75		245	8.8
	Shutter	Number	5%	0	12.5			0.12	1.5							1.5		237.5	1.5
	Shutter guide	Number	1%	0	5			0.008	0.04							0.04		495	0.0
	Cylinder plates	Number	1%	0	5			0.85	4.25							4.25		495	4.3
	Shaft	Number	60%	1	300			7.5	2250							2250		200	2250.0
	Concave adjuster/holder	Number	3%	0	30							0.18	5.4			5.4		970	5.4
	Wire rope	Number	5%	0	25			0.25	6.25							6.25		475	6.3
	Sieve	Number	20%	1	150					0.05	7.5					7.5		600	7.5
							20		***2262.04***		***43.5***		***44.15***		***12.5***	***2362.19***			*2362.2*
Cascading process	Materials (taken-back product)	Number			250			45.9762	11494.05	17.119	4279.75	4.1877	1046.925	0.099	24.75	16845.48	95%	16,044.44	801.0
	Fasteners	Number	2%	1	240					0.1	24					24		11760	24.0
	Bearings	Number	1%	0	10							0.12	1.2			1.2		990	1.2
	Grease	Litres	30%	0	6	0.024	6									0			0.0
	Bushings	Number	1%	0	10					0.03	0.3					0.3		990	0.3
							6		***0***		***24.3***		***1.2***		***0***	***25.5***			*25.5*

Table A3: Inventory of parts and materials requirements by each PLET

Tables A4.1- A4.5 shows the resource requirements by each PLET in terms of quantity and cost.

Item No.	Direct Materials Part/material	Measurement	Quantity required	Average unit price	Total cost
1	Materials (taken-back product)	Number	250	180.00 DM	*45,000.00 DM*
	Indirect Materials				
2	Fasteners	Number	600	0.20 DM	120.00 DM
3	Bearings	Number	20	10.00 DM	200.00 DM
4	Grease	Litres	20	12.00 DM	240.00 DM
5	Bushings	Number	10	1.50 DM	15.00 DM
6	Belts	Number	5	5.00 DM	25.00 DM
					600.00 DM
	Labour				
	Item	**Measurement**	**Quantity required**	**Average wage**	**Total cost**
1	Direct labour[#]	Man-hours	100	25.00 DM	*2,500.00 DM*
2	Indirect labour[+]	Man-hours	15	35.00 DM	*525.00 DM*
	Energy				
	Item	**Measurement**	**Quantity required**	**Cost per unit**	**Total cost**
1	Electricity	KWh	4000	0.39 DM	1,572.00 DM
2	Diesell	Ton	3	1,590.00 DM	4,770.00 DM
					6,342.00 DM
	Other resources				
1	Compressed air	Ton	2.5	50.00 DM	*125.00 DM*

Table A4.1: Maintenance process cost summaries

Item No.	Materials Part	Measurement	Quantity required	Average unit price	Total cost
1	Materials (taken-back product)	Number	250	180.00 DM	*45,000.00 DM*
	Indirect Materials				
2	Fasteners	Number	600	0.20 DM	120.00 DM
3	Bearings	Number	50	10.00 DM	500.00 DM
4	Grease	10kg tins	20	12.00 DM	240.00DM
5	Bushings	Number	200	1.50 DM	300.00 DM
6	Belts	Number	25	5.00 DM	125.00 DM
					1,285.00 DM
	Labour				
	Item	**Measurement**	**Quantity required**	**Average wage**	**Total cost**
1	Direct labour	Man-hours	138	25.00 DM	*3,438.00 DM*
2	Indirect labour	Man-hours	21	35.00 DM	*722.00 DM*
	Energy				
	Item	**Measurement**	**Quantity required**	**Cost per unit**	**Total cost**
1	Electricity	KWh	5000	0.39 DM	1,965.00 DM
2	Diesel	Ton	3	1,590.00 DM	4,770.00 DM
					6,735.00 DM
	Other resources				
1	Compressed air	Ton	3.2	50.00 DM	*160.00 DM*

Table A4.2: Refurbishing process cost summaries

	Direct Materials				
Item No.	**Part**	**Measurement**	**Quantity required**	**Average unit price**	**Total cost**
1	Materials (taken-back product)	Number	250	180.00 DM	*45,000.00 DM*
	Indirect Materials				
2	Fasteners	Number	600	0.20 DM	120 DM
3	Bearings	Number	250	10.00 DM	2,500 DM
4	Grease	Litres	20	12.00 DM	240 DM
5	Bushings	Number	900	1.50 DM	1,350 DM
6	Belts	Number	250	5.00 DM	1,250 DM
7	Pulleys	Number	15	8.00 DM	120 DM
					5,580 DM
	Other Direct Materials				
8	Concave	Number	12.5	25.00 DM	313.00 DM
9	Shutter	Number	2.5	2.00 DM	5.00 DM
10	Shutter guide	Number	5	0.52 DM	3.00 DM
11	Cylinder plates	Number	300	10.00 DM	3,000.00 DM
12	Shaft	Number	15	12.00 DM	180.00 DM
13	Concave adjuster/holder	Number	50	2.00 DM	100.00 DM
14	Wire rope	Number	100	6.00 DM	600.00 DM
15	Sieve	Number	7.5	20.00 DM	150.00 DM
					4,350.00 DM
	Labour				
	Item	**Measurement**	**Quantity required**	**Average wage**	**Total cost**
1	Direct labour	Man-hours	165	25.00 DM	*4,115.00 DM*
2	Indirect labour	Man-hours	25	30.00 DM	*741.00 DM*
	Energy				
	Item	**Measurement**	**Quantity required**	**Cost per unit**	**Total cost**
1	Electricity	KWh	5500	0.39 DM	2,161.50 DM
2	Diesel	Ton	3	1,590.00 DM	4,770.00 DM
					6,931.50 DM
	Other resources				
1	Compressed air	Ton	2.5	50.00 DM	*125 DM*

[#] *Quantity of direct labour is computed from each departmental requirement in the expected current cost table*

[+] *Indirect labour calculated as 15% of direct labour*

Table A4.3: Remanufacturing process cost summaries

	Direct Materials				
Item No.	**Part**	**Measurement**	**Quantity required**	**Average unit price**	**Total cost**
1	Materials (taken-back product)	Number	250	180.00 DM	*45,000.00 DM*
	Indirect Materials				
2	Fasteners	Number	0	0.20 DM	0.00 DM
3	Bearings	Number	600	10.00 DM	6,000.00 DM
4	Grease	Litres	20	12.00 DM	240.00 DM
5	Bushings	Number	20	1.50 DM	30.00 DM
6	Belts	Number	900	5.00 DM	4,500.00 DM
					10,770.00 DM
	Other Direct Materials				
7	Concave	Number	250	25.00 DM	6,250.00 DM
8	Shutter	Number	5	2.00 DM	10.00 DM
9	Shutter guide	Number	12.5	0.52 DM	7.00 DM
10	Cylinder plates	Number	5	10.00 DM	50.00 DM
11	Shaft	Number	5	12.00 DM	60.00 DM
12	Concave adjuster/holder	Number	300	2.00 DM	600.00 DM
13	Wire rope	Number	30	6.00 DM	180.00 DM
14	Sieve	Number	25	20.00 DM	500.00 DM
					7,657.00 DM
	Labour				
	Item	**Measurement**	**Quantity required**	**Average wage**	**Total cost**
1	Direct labour	Man-hours	144	25.00 DM	*3,594.00 DM*
2	Indirect labour	Man-hours	22	35.00 DM	*755.00 DM*
	Energy				
	Item	**Measurement**	**Quantity required**	**Cost per unit**	**Total cost**
1	Electricity	KWh	4000	0.39 DM	1,572.00 DM
2	Diesel	Ton	3	1,590.00 DM	4,770.00 DM
					6,342.00 DM
	Other resources				
1	Compressed air	Ton	2.5	50.00 DM	*125.00 DM*

Table A4.4: Upgrading process cost summaries

	Materials				
Item No.	**Part**	**Measurement**	**Quantity required**	**Average unit price**	**Total cost**
1	Materials (taken-back product)	Number	250	180.00 DM	*45,000.00 DM*
	Indirect Materials				
2	Fasteners	Number	240	0.20 DM	48.00 DM
3	Bearings	Number	10	10.00 DM	100.00 DM
4	Grease	Litres	6	12.00 DM	72.00 DM
5	Bushings	Number	10	1.50 DM	15.00 DM
					235.00 DM
	Labour				
	Item	**Measurement**	**Quantity required**	**Average wage**	**Total cost**
1	Direct labour	Man-hours	113	25.00 DM	*2,813.00 DM*
2	Indirect labour	Man-hours	17	35.00 DM	*591.00 DM*
	Energy				
	Item	**Measurement**	**Quantity required**	**Cost per unit**	**Total cost**
1	Electricity	KWh	2500	0.39 DM	982.50 DM
2	Diesel	Ton	3	1,590.00 DM	4,770.00 DM
					5,752.50 DM
	Other resources				
1	Compressed air	Ton	2.5	50.00 DM	*125.00 DM*

Table A4.5: Cascading process cost summaries

Appendix B: Cost data collection module (Codacol)

This is a questionnaire for cost data collection and contains part of the cost information extracted from Tables A3.1 – A3.5 and A4.1 – A4.2 that are used in PLETs' evaluation on the case study.

1. What is the average quantity of products worked in the following department for each PLET in this period? (Enter the values in to Table B1).

PLET option	**Department**							
	Pretreatment Logistics	Inspections	Disassembly	Sorting	Cleaning	Reconditioning	Reassembly	Testing
Repair	250	250	250	-	250	235	235	235
Refurbishing	250	250	248	-	248	235	230	230
Remanufacturing	250	250	248	248	248	246	246	246
Upgrading	250	250	248	248	248	245	243	243
Cascading	250	250	250	250	250	250	250	250

Table B1: Reworked product quantity table

2. What is the cost of the listed items used in the following departments for each of these PLET options in the period? (Enter values into Table B2).

PLET option	**Item**	**Department**							
		Pretreatment Logistics	Inspections	Disassembly	Sorting	Cleaning	Reconditioning	Reassembly	Testing
Repair	Materials	45,000 DM							
	Labour	104 DM	521 DM	625 DM	0 DM	313 DM	521 DM	417 DM	208 DM
	Overhead	1,746.16 DM	456 DM	1,139 DM	0 DM	911 DM	456 DM	1,215 DM	607 DM
Refurbishing	Materials	45,000 DM							
	Labour	104 DM	729 DM	1,042 DM	0 DM	313 DM	729 DM	625 DM	208 DM
	Overhead	2,047.43 DM	534 DM	1,335 DM	0 DM	1,068 DM	534 DM	1,424 DM	712 DM
Remanufacturing	Materials	45,000 DM						4,350 DM	
	Labour	104 DM	1,042 DM	1,042 DM	313 DM	365 DM	1,042 DM	625 DM	208 DM
	Overhead	2,675.43 DM	803 DM	2,007 DM	803 DM	1,605 DM	803 DM	2,007 DM	1,070 DM
Upgrading	Materials	45,000 DM						7,657 DM	
	Labour	104 DM	521 DM	1,042 DM	313 DM	365 DM	521 DM	625 DM	208 DM
	Overhead	4,138.09 DM	1,080 DM	2,699 DM	900 DM	2,159 DM	1,080 DM	2,159 DM	1,259 DM
Cascading	Materials	45,000 DM							
	Labour	104 DM	313 DM	1,042 DM	417 DM	313 DM	313 DM	104 DM	208 DM
	Overhead	1,665.15 DM	486 DM	1,388 DM	347 DM	833 DM	486 DM	694 DM	486 DM

Table B2: Departmental (materials, labour and overhead) costs scoring table

3. What percentage of prime cost of goods processed is charged as the administrative cost for each PLET? (Enter the values into Table B4).

Repair	Refurbishing	Remanufacturing	Upgrading	Cascading
5%	5%	7%	6%	5%

Table B3: Administrative and general cost scoring table

4. Enter the percentage of prime cost of goods processed is charged as the sales overhead for each PLET in Table B4.

Repair	Refurbishing	Remanufacturing	Upgrading	Cascading
5%	5%	7%	6%	5%

Table B4: Sales overhead scoring table

5. Enter the quantity of the product is expected to be sold in the period Table B5.

Repair	Refurbishing	Remanufacturing	Upgrading	Cascading
235	230	246	243	250

Table B5: Sales quantity scoring table

6. What is the estimated market value of the product based on the qualities impacted to it by the each PLET option? (Enter the values into Table B6).

Repaired	Refurbished	Remanufactured	Upgraded	Cascaded
250.00 DM	280.00 DM	300.00 DM	350.00 DM	180.00 DM

Table B6: Estimated market value of reworked product scoring table

7. What is the average cost of disposing off a unit of the product? (Enter the value in the space provided below).

130.00 DM

8. If your minimum standard on cost is to be cost element based, then enter the allowable maximum cost on each of the following operations of the PLET (Enter the values into Table B7).

Department							
Pretreatment Logistics	Inspections	Disassembly	Sorting	Cleaning	Reconditioning	Reassembly	Testing
200.00 DM	8.00 DM	16.00 DM	5.00 DM	12.00 DM	8.00 DM	12.00 DM	6.50 DM

Table B7: Allowable maximum cost scoring table

Appendix C: Technical data collection module (Tedacol)

This is the section of a questionnaire for technical data collection and the technical data used in PLETs' evaluation on the case study.

1. Product complexity is here used to express the difficulty involved in carrying out a PLET on the product and is evaluated in terms of number because of Comparing the PLET options in view of the available resources, enter the complexity score of the product with respect to each of the PLETs into Table C2 by using Table C1.

Product complexity	**Complexity rating T_{CXT}**
Very high	0.1
High	0.3
Average	0.5
Simple	0.7
Very simple	0.9

Table C1: Product complexity rating with regard to ease of handling by the PLET option

Product complexity score of the PLET T_{CXT} :

Repair	**Refurbishing**	**Remanufacturing**	**Upgrading**	**Cascading**
0.9	0.7	0.5	0.5	0.9

Table C2: Product complexity scoring table

2. Comparing the PLET options in view of the available resources, score the product condition with respect to each of the PLETs into Table C4 by using table C3?

Product condition	**Suitability**	**Condition rating T_{PDCD}**
Very bad	Absolutely unsuitable	0.1
Bad	Unsuitable	0.3
Average	Manageable	0.5
Good	Acceptable	0.7
Very good	Perfect	0.9

Table C3: Product condition rating with regard to suitability for the PLET option

The PLET score with regard to product condition T_{PDCD}:

Repair	Refurbishing	Remanufacturing	Upgrading	Cascading
0.9	0.9	0.7	0.7	0.9

Table C4: Product condition scoring table

3. Comparing the PLET options, score (in Table C6) the thoroughness requirement of each of the PLET to meet the required standard using Table C5.

Thoroughness requirement	Required thoroughness rating T_{Thrr}
Very high	0.1
High	0.3
Average	0.5
Simple	0.7
Very simple to none	0.9

Table C5: Thoroughness requirement rating

PLET option	PLET operations *op*:							
	Pretreatment Logistics	Diagnosis	Disassembly	Sorting	Cleaning	Recondition	Reassembly	Test
Repair	0.3	0.7	0.7	-	0.7	0.7	0.7	0.7
Refurbishing	0.3	0.5	0.5	-	0.5	0.3	0.5	0.5
Remanufacturing	0.1	0.1	0.1	0.1	0.1	0.1	0.1	0.1
Upgrading	0.1	0.3	0.3	0.5	0.3	0.1	0.1	0.1
Cascading	0.5	0.9	0.5	0.5	0.7	0.7	0.9	0.9

Table C6: Thoroughness requirement scoring table

4. In view of the product configuration and condition, use Table C7 to evaluate the required diagnostic intensity to carry out the PLET option. Enter the scores in Table C8.

Required diagnostic intensity	Diagnosis rating T_{dagr}
Very high	0.1
High	0.3
Average	0.5
Simple	0.7
Very simple to no diagnosis	0.9

Table C7: Diagnosis intensity requirement and rating

PLET option	Repair	Refurbishing	Remanufacturing	Upgrading	Cascading
Required diagnosis rating	0.7	0.5	0.1	0.1	0.9

Table C8: Diagnosis requirement scoring table

5. Considering the required intensity of disassembly by the PLET option and the types of liaisons that have to be removed, use Tables C9 and C10 to obtain the disassembly score for each of the PLET option. Enter the scores into Table C11.

Liaisons	Ease of dissolution rating T_{eodr}
Clips, pins, plug and retainers	0.95
Bolts, screws, nuts and washers	0.80
Snap fits, press fits	0.65
Rivet	0.50
Adhesives	0.35
Spot welding	0.20
Soldering, brazing and welding	0.05

Table C9: Liaison dissolubility rating

Required disassembly intensity *rdi*		Disassembly requirement rating T_{disrr}
Complete	(*rdi* =100%)	0.1
High	(65% <= *rdi* < 100%)	0.3
Average	(45% <= *rdi* < 65%)	0.5
Little	(25% <= *rdi* < 45%)	0.7
Very little	(*rdi* < 25%)	0.9

Table C10: Reassembly requirement rating

PLET option	Remarks	Liaison type *l*	
		Bolts and nuts	Welding
Repair	Liaison type dissolution rating T_{eodr}	0.8	
	Number of the liaison type per product n_l	36	
	Required intensity (% of the number of parts to dismantle to total number of parts)		0.7
Refurbishing	Liaison type dissolution rating T_{eodr}	0.8	
	Number of the liaison type per product n_l	36	
	Required intensity (% of the number of parts to dismantle to total number of parts)		0.1
Remanufacturing	Liaison type dissolution rating T_{eodr}	0.8	0.1
	Number of the liaison type per product n_l	36	4
	Required intensity (% of the number of parts to dismantle to total number of parts)		0.1
Upgrading	Liaison type dissolution rating T_{eodr}	0.8	0.1
	Number of the liaison type per product n_l	36	4
	Required intensity (% of the number of parts to dismantle to total number of parts)		0.3
Cascading	Liaison type dissolution rating T_{eodr}	0.8	
	Number of the liaison type per product n_l	36	
	Required intensity (% of the number of parts to dismantle to total number of parts)		0.5

Table C11: Disassembly requirement scoring table

6. Using Table C12 below, score (in Table C13) the performance of each PLET on the basis of their sorting requirements.

Sorting method efficiency	Efficiency rating $T_{efrsomd}$
Very high	0.9
High	0.7
Average	0.5
Low	0.3
Very low	0.1

Table C12: Sorting method efficiency rating

PLET option	Sorting method type and rating for each PLET *somd*
	Hand
Repair	-
Refurbishing	-
Remanufacturing	0.9
Upgrading	0.7
Cascading	0.7

Table C13: Sorting requirement scoring table

7. Using Tables C14 and C15, evaluate the cleaning requirements of each PLET to meet the standard. Enter the scores into Table C16.

Effectiveness assessment	Effectiveness rating T_{efr}
Very high	1.00
High	0.75
Average	0.50
Low	0.30
Very low	0.10
Ineffective	0.00

Table C14: Effectiveness rating of methods employed in carrying out an operation

Negative Impact of the method on the product	Impact rating T_{impr}
None	1.00
Very little	0.82
Little	0.64
Medium	0.46
High	0.28
Very high	0.10

Table C15: Impact rating of methods employed in carrying out an operation

PLET option	Remarks	Cleaning method type *clmd*	
		Compressed air	**Dry air**
Repair	Cleaning method type's effic. rating *efr*	0.75	-
	Cleaning method type's impact rating *impr*	1.00	-
Refurbishing	Cleaning method type's effic. rating *efr*	0.75	-
	Cleaning method type's impact rating *impr*	1.00	-
Remanufacturing	Cleaning method type's effic. rating *efr*	0.50	1.00
	Cleaning method type's impact rating *impr*	1.00	1.00
Upgrading	Cleaning method type's effic. rating *efr*	0.50	1.00
	Cleaning method type's impact rating *impr*	1.00	1.00
Cascading	Cleaning method type's effic. rating *efr*	1.00	-
	Cleaning method type's impact rating *impr*	1.00	-

Table C16: Cleaning requirement scoring table

8. Evaluate the reconditioning requirement of each PLET by scoring the required reconditioning intensity and the impact of the reconditioning methods that have to be employed to meet the PLET quality by using Tables C14, C15 and C17. Enter the values into Table C18.

Required reconditioning intensity *rreci*		**Reconditioning requirement rating *recrr***
Complete	(*rdi* =100%)	0.1
High	(65%<= *rdi* < 100%)	0.3
Average	(45% <= *rdi* < 65%)	0.5
Little	(25% <= *rdi* < 45%)	0.7
Very little	(*rdi* < 25%)	0.9

Table C17: Reconditioning requirement rating

PLET option	Remarks	Reconditioning method type *clmd*	
		Straightening/bending	
Repair	Reconditioning method type's effic. rating *efr*	0.75	
	Reconditioning method type's impact rating *impr*	0.82	
	Required Reconditioning intensity rating *recrr*	0.50	(Chosen from Table 10)
Refurbishing	Reconditioning method type's effic. rating *efr*	0.75	
	Reconditioning method type's impact rating *impr*	0.82	
	Required Reconditioning intensity rating *recrr*	0.10	(Chosen from Table 10)
Remanufacturing	Reconditioning method type's effic. rating *efr*	0.50	
	Reconditioning method type's impact rating *impr*	0.82	
	Required Reconditioning intensity rating *recrr*	0.10	(Chosen from Table 10)
Upgrading	Reconditioning method type's effic. rating *efr*	0.50	
	Reconditioning method type's impact rating *impr*	0.82	
	Required reconditioning intensity rating *recrr*	0.30	(Chosen from Table 10)
Cascading	Reconditioning method type's effic. rating *efr*	1.00	
	Reconditioning method type's impact rating *impr*	0.82	
	Required Reconditioning intensity rating *recrr*	0.50	(Chosen from Table 10)

Table C18: Reconditioning requirement scoring table

9. Considering the required intensity of reassembly by the PLET option and the types of liaisons that have to be employed, use Tables C19, C20 and C21 to obtain the reassembly score for each of the PLET option. Enter the value into Table C22.

Liaisons	Ease of reassembleability rating *eorr*
Rivet	0.95
Clips, pins, plug and retainers	0.80
Bolts, screws, nuts and washers	0.75
Snap fits, press fits	0.65
Spot welding	0.35
Adhesives	0.20
Soldering, brazing and welding	0.05

Table C19: Liaison reassembleability rating

Parts and liaisons	Reuseability rating *rurp*
1. Both parts of the joint and the liaisons are reusable without rework	1.00
2. The parts are reusable without rework and the liaisons reusable with minor rework	0.85
3. Only the two parts of the joint are reusable without rework	0.70
4. One part is reusable without rework and the other part reusable after some rework	0.50
5. Only one of the parts of the joint are reusable without rework	0.30
6. Only one part is reusable after some rework	0.10
7. No part is reusable	0.00

Table C20: Reusability rating of parts to a joint

Required reassembly intensity *rri*		Reassembly requirement rating *rerr*
Complete	(*rri* =100%)	0.1
High	(65% <= *rri* < 100%)	0.3
Average	(45% <= *rri* < 65%)	0.5
Little	(25% <= *rri* < 45%)	0.7
Very little	(*rri* < 25%)	0.9

Table C21: Reassembly requirement rating

PLET option	Remarks	Joint/liaison type *jt*			
		Bolts & nuts	Snap fits	Welding	
Repair	Joint/part type reassembly rating *eorr*	0.75		0.05	
	Number of the joint/part type per product n_{jt}	36		4	
	Joint/part type reusability rating *eorr*	1.00		0.70	
	Reusable number of the joint/part type per product n_{rjt}	29.00		4	
	Reassembly intensity requirement rating *rerr* :		0.7		(Choose from Table 13)
Refurbishing	Joint/part type reassembly rating *eorr*	0.75		0.05	
	Number of the joint/part type per product n_{jt}	36		4	
	Joint/part type reusability rating *eorr*	1.00		0.70	
	Reusable number of the joint/part type per product n_{rjt}	24		4	
	Reassembly intensity requirement rating *rerr* :		0.1		(Choose from Table 13)
Remanufacturing	Joint/part type reassembly rating *eorr*	0.75		0.05	
	Number of the joint/part type per product n_{jt}	36		4	
	Joint/part type reusability rating *eorr*	1.00		0.70	
	Reusable number of the joint/part type per product n_{rjt}	20		2	
	Reassembly intensity requirement rating *rerr* :		0.1		(Choose from Table 13)
Upgrading	Joint/part type reassembly rating *eorr*	0.75	0.65		
	Number of the joint/part type per product n_{jt}	36	4		
	Joint/part type reusability rating *eorr*	1.00	0.70		
	Reusable number of the joint/part type per product n_{rjt}	20	4		
	Reassembly intensity requirement rating *rerr* :		0.30		(Choose from Table 13)
Cascading	Joint/part type reassembly rating *eorr*	0.75			
	Number of the joint/part type per product n_{jt}	36			
	Joint/part type reusability rating *eorr*	1.00			
	Reusable number of the joint/part type per product n_{rjt}	29			
	Reassembly intensity requirement rating *rerr* :		0.50		(Choose from Table 13)

Table C22: Reassembly requirement scoring table

11. Based on the number of modules that have to be reworked and/or reassembled when the PLET option is chosen, score the testing requirement of the PLET by using Tables C14 and C15. Enter the values into Table C23.

PLET option	**Remarks**	**Testing method type *tesmd***				
		Throughput	**Shelling effic.**	**% Breakage**	**Separation effic.**	**Functionality**
Repair	Testing method type's effic. rating *efr*	-	-	-	-	1
	Testing method type's impact rating *impr*	-	-	-	-	1
Refurbishing	Testing method type's effic. rating *efr*	-	1	1	1	-
	Testing method type's impact rating *impr*	-	1	1	1	-
Remanufacturing	Testing method type's effic. rating *efr*	1	1	1	1	-
	Testing method type's impact rating *impr*	1	1	1	1	-
Upgrading	Testing method type's effic. rating *efr*	1	1	1	1	-
	Testing method type's impact rating *impr*	1	1	1	1	-
Cascading	Testing method type's effic. rating *efr*	-	-	-	-	1
	Testing method type's impact rating *impr*	-	-	-	-	1
Minimum standard	Testing method type's effic. rating *efr*	-	-	-	-	-
	Testing method type's impact rating *impr*	-	-	-	-	-

Table C23: Testing requirement scoring table

12. Considering various resources required by individual PLET, evaluate the suitability of the available resources for the PLET option by using Table C24. Enter the values into Table C25.

If	**Then it is**	**Suitability rating *resr***
$T_p >= T_r$	Good	0.9
$T_p < T_r$ but there is T_{af}	Fair	0.5
$T_p < T_r$ but there is unaffordable T_{av}	Bad	0.1
$T_p < T_r$ but there is no T_{av}	Impossible	0.0

Table C24: Techno-availability status ratings

PLET option	**Remarks**	**Resource type *typ***	
		Machinery	Utility
Repair	Resource type's suitability rating $resr_{typ}$	0.90	0.90
Refurbishing	Resource type's suitability rating $resr_{typ}$	0.90	0.90
Remanufacturing	Resource type's suitability rating $resr_{typ}$	0.90	0.75
Upgrading	Resource type's suitability rating $resr_{typ}$	0.50	0.75
Cascading	Resource type's suitability rating $resr_{typ}$	0.90	0.90

Table C25: Resource suitability scoring table

Appendix D: Environmental data collection module (Endacol)

This questionnaire is to be used for the evaluation of the environmental friendliness of each process that can be used to extend the lifecycle of a product. Enter/supply the following data where relevant, an estimate is acceptable in case the actual data is not available. Note: Under resource consumption and resource conservation calculations, all units of each resource type (except electricity) have to be converted to Kg.

1. What is the number/quantity of products expected to be completed in the period by the PLET option? Enter the value into Table D1 below.

Repair	Refurbishing	Remanufacturing	Upgrading	Cascading
235	230	246	243	250

Table D1: Quantity of reworked product data collection table

a. Material consumption

2. Enter the estimate quantity of each non-toxic material type to be used for each PLET into Table D2 below.

PLET option	Material type *r* consumed per period				
	Galvanized steel	Mild steel	Carbon steel	Rubber	Lubricant
Repair	0.00	9.30	2.40	0.25	1.60
Refurbishing	0.00	15.00	6.00	1.25	20.00
Remanufacturing	309.34	142.00	168.75	12.50	20.00
Upgrading	2262.04	43.50	44.15	12.50	20.00
Cascading	0.00	24.30	1.20	0.00	6.00
Allowable maximum	45.00	39.50	0.72	0.15	0.08

Table D2: Non-toxic material consumption data collection table

b. Energy consumption

3. By entering the electrical energy ratings of equipment meant for each PLET option into Table D3, estimate the energy consumption in each case.

PLET option	Estimated total consumption rate by all facilities used for the PLET	Estimated time of use per period
Repair	2.8	308
Refurbishing	3	396
Remanufacturing	3	465
Upgrading	3	444
Cascading	2	340
Allowable consumption per product	6	

Table D3: Electrical energy consumption data collection table

4. Enter the estimated quantity of gas/compressed air consumed per period for the individual PLET option into Table D4 below.

PLET option	Estimated total consumption rate by all facilities used for the PLET	Estimated time of use per period
Repair	6	308
Refurbishing	6	396
Remanufacturing	6	465
Upgrading	6	444
Cascading	6	340
Allowable max consumn. per product	0.08	

Table D4: Gas/compressed air consumption data collection table

B. Resource conservation

5. Estimate the quantity of the following resources saved by using PLET option by entering values of each of the following item in to Tables D5, D6 and D7 correspondingly.

i. Material conservation value:

PLET option	Material type	Galvanized Steel	Mild steel	Carbon steel	Lubricants	Rubber
	Quantity of material type required to produce a virgin product	45	39.500	0.750	0.080	0.015
Repair	Quantity of material type required to repair the product		0.312	0.086	0.080	
Refurbishing	Quantity of material type required to refurbish the product		0.312	0.086	0.240	
Remanufacturing	Quantity of material type required to remanufacture the product	3.716	0.668	1.118	0.240	0.015
Upgrading	Quantity of material type required to upgrade the product	1.359	0.332	0.024	0.450	0.015
Cascading	Quantity of material type required to cascade the product		0.601	0.024	0.027	
Required minimum	Required minimum quantity of material type to be spared	0.45	0.395	0.0075	0.0008	0.00015

Table D5: Materials conservation data collection table

ii. Energy conservation value:

PLET option	Energy type	Electrical
	Quantity of energy type required to produce a virgin product	6.000
Repair	Quantity of energy type required to repair the product	3.670
Refurbishing	Quantity of energy type required to refurbish the product	5.165
Remanufacturing	Quantity of energy type required to remanufacture the product	5.671
Upgrading	Quantity of energy type required to upgrade the product	5.481
Cascading	Quantity of energy type required to cascade the product	2.720
Required minimum	Required minimum quantity of energy type to be spared	0.060

Table D6: Energy conservation data collection table

iii. Compressed air/gas conservation value:

PLET option	Remarks	Value
	Quantity of air required to produce a virgin product	0.080
Repair	Quantity of air required to repair the product	3.670
Refurbishing	Quantity of air required to refurbish the product	5.165
Remanufacturing	Quantity of air required to remanufacture the product	5.671
Upgrading	Quantity of air required to upgrade the product	5.481
Cascading	Quantity of air required to cascade the product	2.720
Required minimum	Required reduction in quantity of air consumption	0.008

Table D7: Gas/compressed air conservation data collection table

C. Waste release

6. Estimate the quantity of each of the following classes of waste expected to be released by individual PLET option into Table D8 below.

PLET option	Solid waste	Gaseous emissions
Repair	0.295	0.063
Refurbishing	1.107	0.092
Remanufacturing	2.038	0.019
Upgrading	2.044	0.026
Cascading	0.890	0.061
Allowable release	2.038	0.099

Table D8: Quantity of waste release data collection table

D. Environmental Impact Indication of waste release

7. Enter the threshold value and the quantity of each constituent pollutant released by individual PLET into Table D9 below.

PLET option	Waste constituent			
	Dust	Iron	Carbon	Zinc
Repair	0.319	0.201	0.007	0.003
Refurbishing	0.326	0.320	0.011	0.006
Remanufacturing	0.305	0.480	0.010	0.004
Upgrading	0.309	0.430	0.089	0.004
Cascading	0.300	0.190	0.006	0.001
LD_{50}	0.500	0.400	0.050	0.003
Allowable constituent release	0.495	0.396	0.0495	0.007

Table D9: Environmental impact data collection table

Appendix E: Market data collection module (Madacol)

This appendix consists of the questionnaire used for PLETs' evaluation with regard to the market.

1. Enter the average value or (if such data is not available) rate the volume of these materials that could be available for use in the specific period under consideration. Enter the values into Table E2.

Supply quantity (subjective)	**Supply quantity rating** *sqs*
Abundant	0.9
Large	0.7
Medium	0.5
Low	0.3
Very low	0.1

Table E1: Subjective supply volume rating

PLET option	**Part/material type**			
	Product to be taken back	Electric motors	Carbon tool steel	Galvanized steel
Repair	0.5	0.5	0.5	0.5
Refurbishing	0.5	0.5	0.5	0.5
Remanufacturing	0.5	0.5	0.5	0.5
Upgrading	0.5	0.5	0.5	0.5
Cascading	0.5	0.5	0.5	0.5
Required minimum	0.5	0.5	0.5	0.5

Table E2: Subjective supply volume scoring table

2. Employ Table E3 to assess the ease with which materials and parts can be worked by using the facilities available for the PLET option. Enter the values into Table E4.

Ease of working	**Ease of working (reworkability) rating** *wos*
Very easy	1.0
Easy	0.75
Moderately easy	0.5
Difficult	0.3
Very difficult	0.1

Table E3: Parts and materials workability rating

PLET option	Workability rating of the part/material type wos_{pr}	
	Product to be taken back	Others
Repair	0.75	0.75
Refurbishing	0.75	0.75
Remanufacturing	0.50	0.25
Upgrading	1.00	1.00
Cascading	0.75	0.75
Required minimum standard	0.75	0.78

Table E4: Parts and materials workability scoring table

3. Using Table E5, assess the degree of dimensional, performance and safety conformity of parts and materials needed for each PLET option. Enter the values into Tables E6, E7 and E8 as appropriate.

Degree of conformity	Remark	Supply conformity indices *ddci, dpci, dsci*
Meets the required standard	Excellent	1.0
Manageable after some modification	Average	0.5
Unfit for the purpose	Poor	0.0

Table E5: Conformity to required specification rating

PLET option	Dimensional conformity index of the part
Repair	1.0
Refurbishing	1.0
Remanufacturing	0.5
Upgrading	0.5
Cascading	1.0
Required minimum standard	0.5

Table E6: Supply's dimensional specification index scoring table

PLET option	Performance conformity index of the part/material
Repair	0.5
Refurbishing	0.5
Remanufacturing	-
Upgrading	1.0
Cascading	0.5
Required minimum standard	0.5

Table E7: Supply's performance specification index scoring table

PLET option	Safety conformity index of the part/material	
	Taken-back product	Others
Repair	1.0	0.5
Refurbishing	1.0	0.5
Remanufacturing	0.5	0.5
Upgrading	0.5	1.0
Cascading	1.0	0.5
Required minimum standard	0.5	0.5

Table E8: Supply's safety specification index scoring table

4. Estimate the volume of reworked product by the PLET option that will likely be demanded in the given period under consideration (use Table E9 when relevant data are not available). Enter the values into Table E10.

Demand quantity (subjective)	Demand quantity rating *dqs*
Very large	0.9
Large	0.7
Medium	0.5
Low	0.3
Very low	0.1

Table E9: Subjective demand volume rating

PLET option	Subjective demand volume assessment value
Repair	0.3
Refurbishing	0.3
Remanufacturing	0.5
Upgrading	0.7
Cascading	0.5
Required minimum volume of demand (subjective)	0.5

Table E10: Demand volume scoring table

5. Using Table E11, assess the degree of conformity of the PLET option reworked product to the following demand quality specifications. Enter the values into Tables E12, E13 and E14.

Degree of conformity	**Demand specification conformity index** *ddci, dpci, dsci*
Meets the required standard	1.0
Manageable after some modifications	0.5
Unfit for the purpose	0.0

Table E11: Demand specification conformity to required specification rating

PLET option	**Dimensional conformity index of the product**
Repair	0.5
Refurbishing	0.5
Remanufacturing	1.0
Upgrading	1.0
Cascading	0.5
Required minimum standard	0.5

Table E12: Dimensional specification index scoring table

PLET option	**Performance conformity index of the product**
Repair	0.5
Refurbishing	0.5
Remanufacturing	1.0
Upgrading	1.0
Cascading	0.5
Required minimum standard	0.5

Table E13: Performance specifications index scoring table

PLET option	**Safety conformity index of the product**
Repair	0.5
Refurbishing	0.5
Remanufacturing	1.0
Upgrading	1.0
Cascading	0.5
Required minimum standard	0.5

Table E14: Safety specifications index scoring table

Appendix F: Time data collection module (Tidacol)

This appendix is the questionnaire used for PLETs' evaluation with regard to process time.

1. What is the average number of hours making up your (planned) workday? Enter the value in the box provided below.

   [8] hours

2. Compute the average set up time for each operation making up the PLET option. Enter the values into Table F1.

PLET option	**PLET operation and their respective setup time in minutes**								
	Pretreatment logistics	Inspection	Disassembly	Sorting	Cleaning	Reconditioning	Incorporation/ Replacement	Reassembly	Testing
Repair	1.0	2.0	2.0	-	2.0	4.0	1.0	2.0	1.0
Refurbishing	1.0	2.5	2.5	-	2.0	5.0	1.5	2.5	1.5
Remanufacturing	2.0	4.0	4.0	1.0	4.0	7.0	0.2	0.3	2.0
Upgrading	1.5	4.0	4.0	1.0	3.0	4.0	0.2	0.35	2.0
Cascading	1.0	2.0	2.0	1.0	2.0	4.0	-	-	1.0
Max allowed time	3.5	6.0	5.0	14.0	3.0	15.0	9.0	-	-

Table F1: Set-up time scoring table

3. Compute the estimate time required to actually carryout each PLET's operations per unit product. Enter the values into Table F2.

PLET option	**PLET operations (in minutes)**								
	Pretreatment logistics	Diagnosis	Disassembly	Sorting	Cleaning	Reconditioning	Incorporation/replacement	Reassembly	Testing
Repair	18	5	10	-	4	7	-	10	3
Refurbishing	18	7	15	-	6	10	-	13	5
Remanufacturing	19	4	14	4	7	12	3	13	8
Upgrading	19	4	14	4	7	12	6	11	9
Cascading	18	4	9	-	4	7	-	10	3
Max allowable time	19	6	16	4	9.5	15	8	14	12

Table F2: Actual operations' time scoring table

4. Estimate the expected auxiliary times (in minutes) likely to be associated with the implementation of each PLET. Enter the values into Table F3.

PLET option	Auxiliary time
Repair	2.0
Refurbishing	2.5
Remanufacturing	3.0
Upgrading	0.4
Cascading	0.3
Max allowable time	3.0

Table F3: Auxiliary time scoring table

5. Estimate delay times (in minutes) likely to be involved in carrying out each of the PLET options. Enter the values in Table F4.

PLET option	Delay time (as % of the workday)
Repair	3.0
Refurbishing	4.0
Remanufacturing	4.0
Upgrading	2.8
Cascading	3.0
Max allowable time	4.0

Table F4: Delay time scoring table

Appendix G: Legislative data collection module (Ledacol)

This questionnaire is to be used to evaluate the degree of conformity of product life extension processes to environmental regulations.
Note: Only the tables that are relevant to this case study are included here.

A. Negative Environmental Indices

1. Estimate the quantity of each type of resources needed per product by each of the PLET option. Enter the values into Tables G1, G2 and G3.

PLET option	Material type consumption (Kg)				
	Galvanized steel	Mild steel	Carbon steel	Rubber	Lubricants
Repair	-	0.04	0.01	0.00	0.00
Refurbishing	-	0.07	0.03	0.01	0.09
Remanufacturing	1.26	0.58	0.69	0.05	0.08
Upgrading	9.31	0.18	0.18	0.05	0.08
Cascading	-	0.10	0.00	-	0.02
Legal standard	4.00	0.70	2.50	0.099	0.008

Table G1: Materials consumption scoring table

PLET option	Energy (electrical) consumption (kWh)
Repair	3.670
Refurbishing	5.165
Remanufacturing	5.671
Upgrading	5.481
Cascading	2.720
Maximum allowable consumption	6.000

Table G2: Energy consumption scoring table

PLET option	Gas/air consumption (Kg)
Repair	7.864
Refurbishing	10.330
Remanufacturing	11.341
Upgrading	10.963
Cascading	8.160
Maximum allowable consumption	0.080

Table G3: Gas consumption scoring table

2. Enter the estimated quantity of waste releases expected from each PLET according to their physical states in Tables G4 and G5.

PLET option	Quantity of solid waste generated (kg)
Repair	0.295
Refurbishing	1.107
Remanufacturing	2.038
Upgrading	2.044
Cascading	0.890
Maximum allowable release	2.038

Table G4: Solid waste releases scoring table

PLET option	Quantity of gaseous emissions (Kg)
Repair	0.063
Refurbishing	0.092
Remanufacturing	0.019
Upgrading	0.026
Cascading	0.061
Maximum allowable emission	0.099

Table G5: Gaseous emissions scoring table

3. Estimate the total quantity of waste constituent/pollutant release by each PLET when analyzed from the wastes generated/emitted. Enter the values into Table G6.

PLET option	Waste constituent/pollutant type and quantity released			
	Dust	Iron	Carbon	Zinc
Repair	0.311	0.200	0.007	0.003
Refurbishing	0.300	0.320	0.011	0.006
Remanufacturing	0.300	0.480	0.010	0.004
Upgrading	0.326	0.430	0.089	0.004
Cascading	0.300	0.190	0.006	0.001
Maximum allowable release	0.495	0.396	0.0495	0.007

Table G6: Waste releases constituents scoring table

B. Positive Environmental Indices

4. Enter the estimated amount of each type of resource savings that individual PLET option is expected to facilitate. Enter the values into Table G7.

PLET option	Resource type and quantity conserved	
	Materials (Kg)	Energy (kWh)
Repair	84.867	2.330
Refurbishing	84.707	0.835
Remanufacturing	79.588	0.329
Upgrading	83.165	0.519
Cascading	84.693	3.280
Required minimum savings	4.500	0.060

Table G7: Resource conservation scoring table