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Maintenance-Centered Sustainability Analysis of Brick and Block Clamp

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ABSTRACT

This paper presents the analysis of the maintenance process effect on the sustainability of a brick and block clamp. Maintenance and refurbishment are essential practices conducted to enhance the sustainability by returning a product to full serviceability and ensuring the safety and usability to prolong the product's life. Reusing a product through maintenance/refurbishment (M/R) reduces the energy involved in procuring new products, thus, minimizing the energy used during the product life cycle and enhancing sustainability. The maintenance-centered sustainability analysis (MCSA) using an energy balance sheet showed various energies involved in the M/R processes and in each clamp part. The estimated total input and recycle/disposal energy of the clamp with M/R was 9.9% and 8.1%, respectively, compared to clamp without M/R. The results show the benefits of M/R from the quantitative perspective of sustainability. MCSA, combined with other strategies, could be used for enhancing sustainability while reducing life-cost of a product.

1. Introduction

Engineers strive in several ways to reduce energy input and costs during product manufacture. Reducing transport distances, insulating factories, buying energy from the lowest cost supplier, and using the most energy-efficient manufacturing techniques are just a hand full of possible solutions.

Maintenance, the process of returning a product back to serviceability, is often overlooked as a solution despite it being able to avoid the need for new products. Additionally, savings can be made on materials extraction, subsequent sourcing and manufacturing energy. All of which were shown to be of great importance in reducing both the ecological and sustainable impact of a product's life cycle[1].

Life cycle analysis (LCA) is generally used to describe the product life cycle, starting from material sourcing to end of life disposal[2]. These analytics are found to be lacking fundamental elements and could be improved with the addition of life cycle elements such as Sustainable Design, Sustainable Transport, Sustainable Maintenance and Sustainable Giveback. These additions are further divided into the Phase 1 and Phase 2 Life Cycle as shown in Table 1[1]. The Phase 1 accommodates energy input, during material sourcing through to manufacture and includes energy spent on transportation of goods to the consumer. The Phase 2 includes all features after delivery to the market: usage, maintenance, disposal and the energy accounting element, giveback.

Though the additions of sustainable design and sustainable transport are often included in the LCA, sustainable maintenance often finds itself isolated and given less attention. Nevertheless, it was illustrated that small improvements in the amounts of energy applied to sustainable maintenance can lead to enormous savings[1]. Returning a product to service, instead of disposal, avoids repetitive usages of energy

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Table 1 Summary of phase 1 and phase 2 life cycle

Phase 1 Life cycle	Phase 2 Life cycle
Sustainable sourcing	Sustainable usage
Sustainable design	Sustainable maintenance
Sustainable manufacture	Sustainable disposal
Sustainable transport	Sustainable giveback

from the Phase 1 Life Cycle.

The proposed system can only prove effectiveness with the addition of a metric system to visualize the benefits, followed by a management strategy to allow for changes to be implemented by the design function. Therefore, the use of the LCA as a platform can be complemented by the implementation of embodied energy (EE) as a metric and an overview management process, total design control management strategy (TDCMS)[1,3,4].

The EE metric has been proposed by several researchers[5-8] and is also adopted by the ISO Environmental Standards Organization (ISO)[9,10]. The application of the metric allows the life cycle input energy to be offset against the saved energy. This is done by attributing each life cycle element with a numerical value for either energy used or energy saved, leading to an energy accounting system. The sustainability analysis in this paper is based on the concept of EE.

TDCMS is an operational management system applied in accordance with ISO14001[9]. This management technique coordinates systems, information and materials flow at a practical level. An overview for executive management is outlined in ISO14044[11].

1.1 Usage-maintenance cycles

The concept of EE can be further demonstrated by considering the maintenance cycle of a product, since maintenance is the most opportune time to collect data relating to component wear and replacement[1]. Fig. 1 indicates how a product enters its first maintenance $\boxed{1}$ after the first period in service. Maintenance is performed and the product is returned to its second life $\boxed{2}$. This sequence continues until the product has undergone several rotations of use and maintenance.

Refurbishment $\boxed{9}$ becomes the end of one cycle and the start of the next providing an as-new product. The steps in this cyclic sequence are laid out as follows: (a) Manufacture; (b) Primary usage; (c) Maintenance (usage-maintenance cycle can repeat); (d) Refurbishment (almost new, the product re-enters cycle); (e) Removal (recycle or dispose) of sacrificial components if they cannot be reused after the maintenance or refurbishment (M/R) $\boxed{8'}$ $\boxed{10'}$; (f) Reuse of a component with a residual life after M/R until the component cannot be reused even with M/R (no residual life).

After the first maintenance, a product is returned to its second usage $\boxed{2}$ where it performs another life in service. Since maintenance has extended the product life, it can be said that a single value of energy primary source (EPS) from Phase 1 life cycle has been saved. The energy used in the maintenance process is small when compared to the large saving of the EPS but should nevertheless be recorded for later use in an energy accounting system. Refurbishment $\boxed{9}$ is much deeper than maintenance $\boxed{1}$ $\boxed{3}$ $\boxed{5}$ $\boxed{7}$ requiring an increased level of energy input which should also be

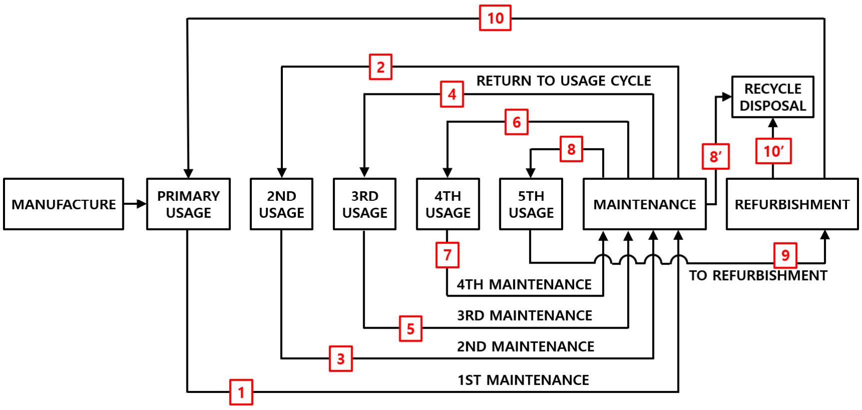


Fig. 1 Usage-maintenance/refurbishment cycle

accounted for. Similar to maintenance, this input is minor when compared to the savings made by prolonging the product life.

By applying maintenance/refurbishment (M/R) processes the used components containing residual life, can be fed backwards into maintenance and re-installed in the product for more than one serviceable life. Yet a definition of residual life of the reused components should be established to ensure reliability[12].

1.2 Energy input to the usage-maintenance cycles

Component flow defines the cycles in Fig. 1, but required energy to complete each process is not considered. Fig. 2 shows the energy accounting cycle, running parallel to the mass flow models while also describing the use of energy within the feed forward and feedback of components. Several differences can be presented regarding Fig. 1: (a) A portion of energy used by the factory during the maintenance period is now clearly shown as the maintenance input energy. Refurbishment is more involved than maintenance, using greater values of energy to accomplish. This is recorded in the refurbishment input energy; (b) Separation of a product's materials for recycling requires energy. Some materials will prove difficult to separate and may not be cost effective. Energy for recycling is recorded as recycle input energy (In cases where recycling is hard to execute, incineration could be most efficient, allowing for the calorific value to be extracted. Carpenter[14] reported that ideally only 80% of waste is recyclable, meaning that 20% of waste cannot be recycled.); (c) Different component flows are clearly illustrated. Part-worn components may retain enough useable life to be used for at least one usage cycle, perhaps in an alternative product. These components are noted as components with a residual life; sacrificial parts, or parts that do not possess the required useable life, will be fed forward into recycling, adding to the recycle input energy value.

The residual life can be estimated using residual embodied energy (REE) assessment based on the energy of primary source (EPS)[1]. Suppose a component taking 100 MJ to source and manufacture, uses 50% of its service life. REE amounts to 50 MJ. Reusing the component should use all or most of the residual Embodied Energy. Any REE will be lost if the component is recycled or disposed prematurely.

The M/R process is a key practice to enhance the sustainability of a product. The effect of the M/R process on its sustainability can be accurately analyzed using maintenance-centered sustainability analysis (MCSA) based on involved energies during the process[1]. The benefit of the M/R process in a brick and block clamp is qualitatively analyzed and reviewed using MCSA technique in the following sections.

2. Maintenance-centered sustainability analysis (MCSA) of brick and block clamp

2.1 Overview

After each maintenance/refurbishment (M/R) period, the M/R data can be reviewed to give a Phase 2 Life Cycle progress report which is useful to see trends in the effectiveness of individual components. This data can give valuable "in-the-field" feedback to the designers who can use the information to influence new designs.

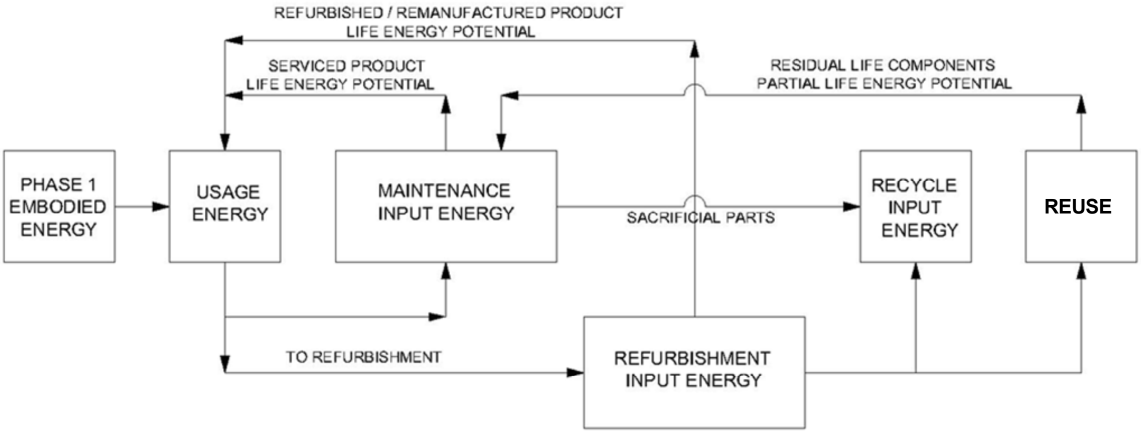


Fig. 2 Energy input to the usage-maintenance/refurbishment cycle

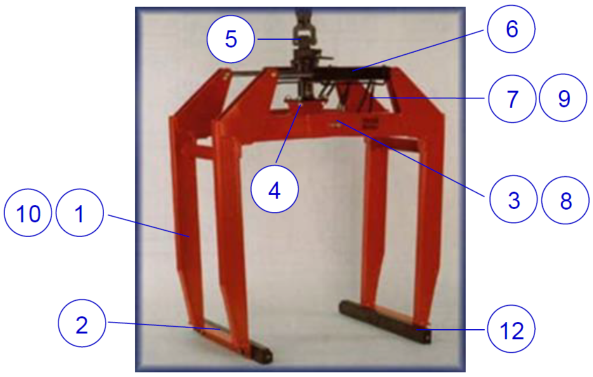


Fig. 3 Brick and block clamp and its components (Courtesy of HE&A Ltd.)[13]

Table 2 Part no. and name of the brick and block clamp

Part No.	Part Name
①	Leg Assembly
②	Gripper Rails
③	Gripper Pins
④	Center Section Assembly
⑤	Hydraulic Rotation Assembly
⑥	Hydraulic Cylinders
⑦	Relief Valve
⑧	Glacier Bushes
⑨	Hydraulic Hoses
⑩	Gated Safety Hooks
⑪	Paint
⑫	Grippers Rubber

Fig. 3 shows the brick and block clamp as it will be used as case study to demonstrate the previously described concepts[13]. The product had been manufactured for several years with no real consideration for the sustainability of its refurbishment. The company created a new design of the clamp in Fig. 3 designed specifically with M/R in mind, enabling the product to be restored to serviceability using less input energy while having a considerably smaller impact on the environment resources than manufacturing a new clamp[13]. This is an excellent example of refurbishment leading to an extended product life and providing a very low sustainability disposal value (SDV). The SDV is the energy required to dispose the product and should be offset against the energy saved by avoiding the procurement of new raw material. The brick and block clamp includes a fabricated steel Leg Assembly ① with Gripper Pins ③, fed by Hydraulic Hoses ⑨. A Grippers Rubber ⑫ is also fitted at the base of the arms. The part no. and names of the all parts are listed in Table 2. A full picture can be obtained at the end of the Total Usage Life (NTL), which is set to be15 ULs.

Table 3 Definition of parameters for the sustainability analysis

Parameter	Definition
EPS	Energy of Primary Source (MJ)
NTL	Total Usage Life
NDL	Design Life per Part
NIP	Cumulative No. of Installed Parts
NRU	Reused Parts Cumulative No.
NRC	Recycled Parts Cumulative No.
REE	Residual Embodied Energy (MJ) **REE = (NIP * NDL − NTL) * EPS (1)**
IPE	Installed Parts Embodied Energy (MJ) **IPE = NIP * EPS (2)**
RUE	Reused Cumulative Energy (MJ) **RUE = NRU * EPS (3)**
RFE	Cumulative Refurbishment Energy (MJ)
MTE	Cumulative Maintenance Energy (MJ)
RCE1	Energy per Single Recycle (MJ)
RCE	Cumulative Recycle Energy (MJ) **RCE = NRC * RCE1 (4)**

The definition of all sustainability analysis parameters to be used in further explanation are listed in Table 3. More details on the parameters are explained in the following sections. Fig. 4(a) shows the life cycle of components with the Design Life (NDL) of 15 ULs (Part ① ② ④ ⑤ ⑩). Suppose the Total Usage Life (NTL) is 15 ULs with the refurbishment period of 5 ULs. The maintenance occurs after each UL. Every cycle of 4 maintenances in a row is followed by a refurbishment, bringing the total maintenance and refurbishment instances (M/R) to 12 and 2 ULs, respectively. Since the mentioned components in this figure are durable enough, they are found to all last throughout the total usage life (NDL = NTL). Only one installation of a new part is needed to have the cumulative no. of installed part of one (NIP = 1). The recycle (or disposal) occurs once (NREC = 1) after the Total Usage Life (NTL = 15 ULs).

Fig. 4(b) shows the life cycle of parts with the Design Life (NDL) of 5 ULs (Part ③ ⑥ ⑦ ⑪). Since the component is not durable enough to last throughout the Total Usage Life (NTL), installation of a new part is needed every NDL (5 ULs) to have three installations (NIP = 3) throughout the Total Usage Life. Four maintenances and reuses occur in every NIP to have 12 reuses (NRU = 12) in total. One

Recycle (or Disposal) occurs every NDL (5 ULs) to have NRC of 3.

2.2 Energy balance sheet (EBS) with M/R

All parameters of the brick and block clamp in Fig. 5 are analyzed by Maintenance-Centered Sustainability Analysis (MCSA) using Energy Balance Sheet (EBS). The energy balance sheets give a good indication of the energy values going into or out of the clamp. The components are shown as a “snapshot” after the Total Usage Life of 15 ULs (NTL = 15). The values in columns 1-4 and 10-12 represent information pre-set by the engineer. The data displayed in columns 9 lists reused (saved) energy, whilst columns 8, 10, 11 and 13 represent input energy to the product.

A list of observations that can be made from Fig. 5 goes as follows: (a) Original Design Life (NDL) is determined by the maintenance engineer: 15 ULs in the case of part ② (Gripper Rails). The part embodies the total energy of 14850 MJ (NIP * NDL * ESP = 1 * 15 * 990) before usage. The embodied energy drops by 990 MJ (EPS) in every usage, and the part cannot be reused anymore after 15 ULs with 0 MJ of REE; (b) Part ③ is a set of four Gripper Pins of which the design life is 5 ULs (NDL). Since the Gripper Pins have experienced 5 ULs after the third installation (NIP = 3), it cannot be reused with zero REE; (c) Part ⑨ is a set of four Hydraulic Hoses with a design life of 2 ULs (NDL). It has an REE of 36 MJ with one UL left after the 8th installations. The third column, Cumulative Number of Installed Parts (NIP), shows the number of new installed parts. Since 8 sets of the part have been installed in total, NIP is 8. The final installed part has not been reused after 15 ULs and is instead recycled with the remaining REE (36 MJ) after the final 15th usage to give NRU of 7; (d) During the total usage life, the Maintenance Energy (MTE) and Refurbishment Energy (RFE) value during the Total Usage Life (15 ULs) values are estimated from the energy consumption (expense) usage during the periods. The average period for each M/R is 5 and 10 days, respectively. MTE and RFE is calculated to be 2510 and 837 MJ, respectively, to have 3347 MJ in total (Fig. 5). The total energy for M/R processes is only 39% of EPS. The cumulative energy for recycle (RCE) of 2551 MJ is calculated from the energy for a single recycle (RCE1) multiplied by NRU of each part. The IPE of the clamp with M/R is slightly increased by 16% over EPS due to the installation of new parts (9923 MJ with M/R vs 8561 MJ of EPS).

Table 4 Comparison of input energies in the life cycle of the clamp (15 ULs) with and without M/R processes

	with M/R (A)		Without M/R (B)		A/B
IPE (MJ)	9923	62.7%	128417	80.4%	7.7%
RCE (MJ)	2551	16.1%	31311	19.6%	8.1%
MTE (MJ)	2510	15.9%	0	0.0%	
RFE (MJ)	837	5.3%	0	0.0%	
Total	15823	100%	159728	100%	9.9%

2.3 Energy balance sheet without M/R

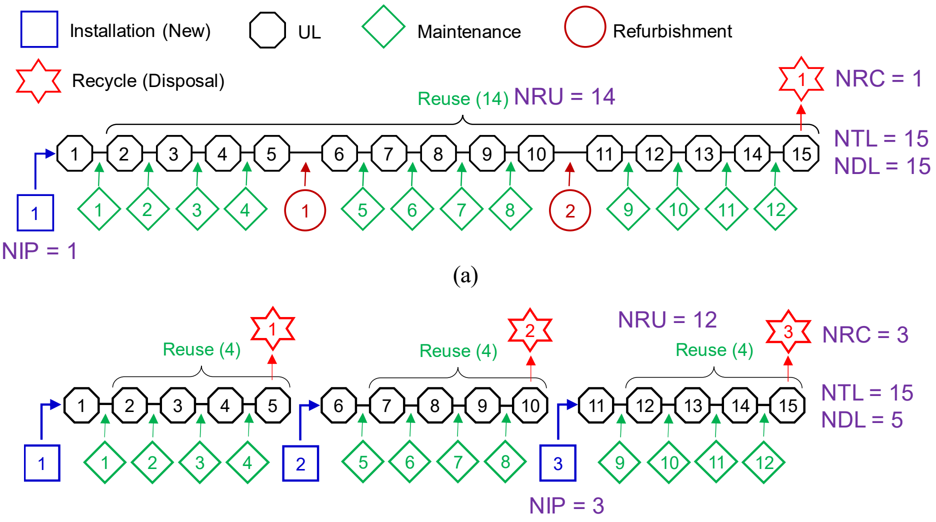
In order to show the benefits of M/R clearly, the energy balance without M/R has been analyzed after 15 ULs (NTL) with the results displayed on Fig. 6. Since the installations (of new parts) and the recycle (of used parts) occurs in each usage, NIP and NRC are set to 15 with no reused parts (NRU = 0). Both MET and RFE are zero due to the absence of M/R. The IPE and RCE is calculated to be 128417 and 31311 MJ, respectively.

2.4 Analysis of input energies with and without M/R

Table 4 summarises various energies from Fig. 4 and 5 throughout the life cycle of the clamp (15 ULs) with and without M/R processes. The clamp with M/R consumes 7.7% of the IPE of one without M/R (9923 vs 128417 MJ) due to less installations of new parts. The RCE of the clamp with M/R is 8.1% of one without M/R (2551 vs 31311 MJ) due to less recycling and more reuses of the parts. The total input energy of the clamp with M/R is 15789 MJ, which is 9.9% of one without M/R (15789 vs 159728 MJ) with a saved energy of 143907 MJ.

In case of the clamp with M/R, IPE occupies 62.7% of the total input energy of the clamp. The ratio is smaller over one without M/R (80.4%) since more portion of energy is used for M/R and recycles happen with less installation of new parts. About 21% of the total input energy is used for M/R (MTE+RFE). The RCE is 8.1% of the counterpart due to the smaller NRC with less recycles and disposals.

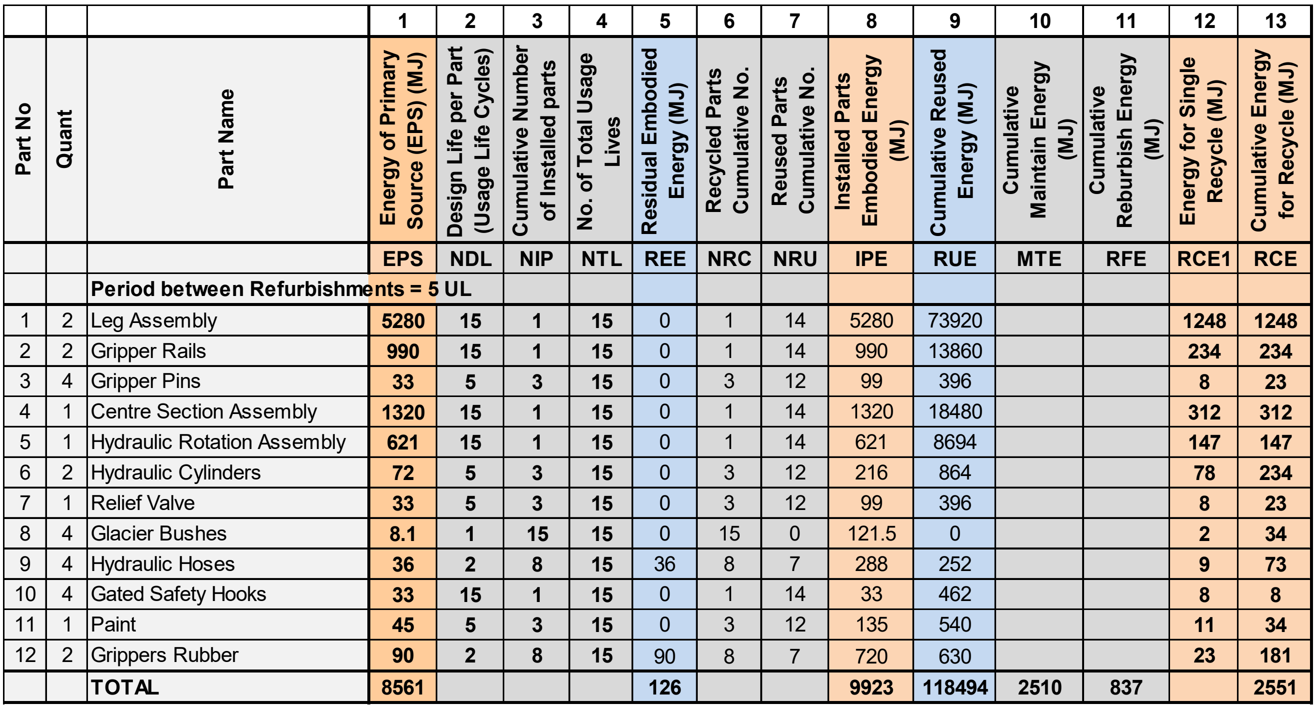
Table 5 compares other energies with and without M/R. Most embodied energy has been consumed through the M/R and reuse processes to have the total REE of 126 MJ with M/R. Yet the unused EE of the clamp without M/R is accumulated in each usage to have an REE 13842 times higher than that of the clamp with M/R.



(a)

(b)

Fig. 4 Life Cycle of the component for (a) NDL = 15 ULs and (b) NDL = 5 ULs (NTL = 15 ULs)



			1	2	3	4	5	6	7	8	9	10	11	12	13
Part No	Quant	Part Name	Energy of Primary Source (EPS) (MJ)	Design Life per Part (Usage Life Cycles)	Cumulative Number of Installed parts	No. of Total Usage Lives	Residual Embodied Energy (MJ)	Recycled Parts Cumulative No.	Reused Parts Cumulative No.	Installed Parts Embodied Energy (MJ)	Cumulative Reused Energy (MJ)	Cumulative Maintain Energy (MJ)	Cumulative Reburbish Energy (MJ)	Energy for Single Recycle (MJ)	Cumulative Energy for Recycle (MJ)
			EPS	**NDL**	**NIP**	**NTL**	**REE**	**NRC**	**NRU**	**IPE**	**RUE**	**MTE**	**RFE**	**RCE1**	**RCE**
		Period between Refurbishments = 5 UL													
1	2	Leg Assembly	**5280**	**15**	**1**	**15**	0	1	14	5280	73920			**1248**	**1248**
2	2	Gripper Rails	**990**	**15**	**1**	**15**	0	1	14	990	13860			**234**	**234**
3	4	Gripper Pins	**33**	**5**	**3**	**15**	0	3	12	99	396			**8**	**23**
4	1	Centre Section Assembly	**1320**	**15**	**1**	**15**	0	1	14	1320	18480			**312**	**312**
5	1	Hydraulic Rotation Assembly	**621**	**15**	**1**	**15**	0	1	14	621	8694			**147**	**147**
6	2	Hydraulic Cylinders	**72**	**5**	**3**	**15**	0	3	12	216	864			**78**	**234**
7	1	Relief Valve	**33**	**5**	**3**	**15**	0	3	12	99	396			**8**	**23**
8	4	Glacier Bushes	**8.1**	**1**	**15**	**15**	0	15	0	121.5	0			**2**	**34**
9	4	Hydraulic Hoses	**36**	**2**	**8**	**15**	36	8	7	288	252			**9**	**73**
10	4	Gated Safety Hooks	**33**	**15**	**1**	**15**	0	1	14	33	462			**8**	**8**
11	1	Paint	**45**	**5**	**3**	**15**	0	3	12	135	540			**11**	**34**
12	2	Grippers Rubber	**90**	**2**	**8**	**15**	90	8	7	720	630			**23**	**181**
		TOTAL	**8561**				**126**			**9923**	**118494**	**2510**	**837**		**2551**

Fig. 5 Energy balance sheet - Brick and block clamp components with the maintenances/refurbishments after total usage life (NTL) of 15 ULs.

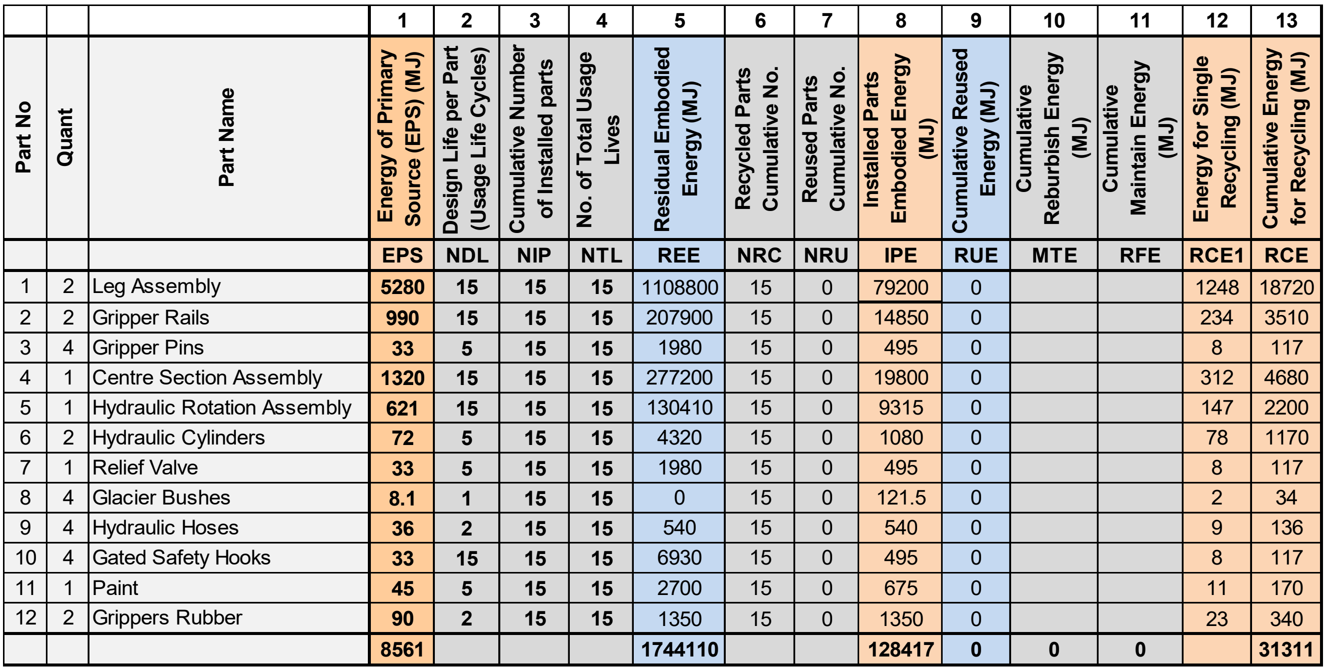
Table 5 Comparison of other energies in the life cycle of the clamp (15 ULs) with and without M/R processes

	With M/R	Without M/R
EPS (MJ)	8561	8561
REE (MJ)	126	1744110
RUE (MJ)	118494	0

2.5 Benefits of Energy Balance Sheet

The real benefit of the EBS is that the life cycle of each element can be analyzed separately. The focus being towards the high energy input values which should be reduced in future products, especially EPS and replacement parts EE. Conversely, elements with high energy savings should be nurtured, such as those shown in the cumulative energy column.

Additional benefits are also found in terms of monetary values. The reduction of input energy automatically reduces



			1	2	3	4	5	6	7	8	9	10	11	12	13
Part No	**Quant**	**Part Name**	**Energy of Primary Source (EPS) (MJ)**	**Design Life per Part (Usage Life Cycles)**	**Cumulative Number of Installed parts**	**No. of Total Usage Lives**	**Residual Embodied Energy (MJ)**	**Recycled Parts Cumulative No.**	**Reused Parts Cumulative No.**	**Installed Parts Embodied Energy (MJ)**	**Cumulative Reused Energy (MJ)**	**Cumulative Reburbish Energy (MJ)**	**Cumulative Maintain Energy (MJ)**	**Energy for Single Recycling (MJ)**	**Cumulative Energy for Recycling (MJ)**
			EPS	**NDL**	**NIP**	**NTL**	**REE**	**NRC**	**NRU**	**IPE**	**RUE**	**MTE**	**RFE**	**RCE1**	**RCE**
1	2	Leg Assembly	**5280**	**15**	**15**	**15**	1108800	15	0	79200	0			1248	18720
2	2	Gripper Rails	**990**	**15**	**15**	**15**	207900	15	0	14850	0			234	3510
3	4	Gripper Pins	**33**	**5**	**15**	**15**	1980	15	0	495	0			8	117
4	1	Centre Section Assembly	**1320**	**15**	**15**	**15**	277200	15	0	19800	0			312	4680
5	1	Hydraulic Rotation Assembly	**621**	**15**	**15**	**15**	130410	15	0	9315	0			147	2200
6	2	Hydraulic Cylinders	**72**	**5**	**15**	**15**	4320	15	0	1080	0			78	1170
7	1	Relief Valve	**33**	**5**	**15**	**15**	1980	15	0	495	0			8	117
8	4	Glacier Bushes	**8.1**	**1**	**15**	**15**	0	15	0	121.5	0			2	34
9	4	Hydraulic Hoses	**36**	**2**	**15**	**15**	540	15	0	540	0			9	136
10	4	Gated Safety Hooks	**33**	**15**	**15**	**15**	6930	15	0	495	0			8	117
11	1	Paint	**45**	**5**	**15**	**15**	2700	15	0	675	0			11	170
12	2	Grippers Rubber	**90**	**2**	**15**	**15**	1350	15	0	1350	0			23	340
			8561				**1744110**			**128417**	**0**	**0**	**0**		**31311**

Fig. 6 Energy balance sheet - brick and block clamp components after 15 ULs without maintenance/refurbishment after total usage life (NTL) of 15 ULs.

cash expenditure and the planned reuse of components with a residual life avoids the waste of discarding useful items before they reach end of life. The saved energy is 143907 MJ (159728-15821 MJ) with an industrial electricity price in South Korea (ROK) of $98 (USD)/MWh[15]. The saved cost per clamp is then calculated to be $3917 (98 * 143907/3600).

The conversion to monetary value creates a more understandable perspective and shows there can be great savings made by the cost focused engineer. The factory in this case study maintains 250 brick and block clamps per year which amount to saving of ~$1M per year.

3. Discussion

The EBS in Table 3 showed input and saved energy values providing the design team with useful information for the redesign of products. EPS accounts for 8561 MJ and could be reduced by better material sourcing, shorter transport distances, recycled material use, more efficient processing, etc. IPE has accrued to a value of 9923 MJ which is the energy value of all the replacement parts applied to the clamp during its 15 ULs. The value is slightly greater than the EPS, but can be considered small since its application has allowed the clamp to be used for 15 ULs. Maintenance allows the clamp to be returned to service amounting to 118494 MJ of RUE. Other high energy usage values include Factory Overhead of 3347 MJ (MTE+RFE) for the maintenance of a single clamp amounting to $91 each or for the 250 clamps per year amounts to $22778.

The factory management reviewed its energy use and discovered that a large portion of this value was used in heating an old and uninsulated factory. Their response was to build discrete heated areas around machining and assembly operations, thus reducing the factory overhead for maintenance operations, plus further reducing their costs for manufacturing of new components.

4. Conclusion

The effect of the maintenance process on the sustainability of a brick and block clamp has been analyzed using MCSA. EBS shows the various energies involved in M/R processes and around in detail. The total input and recycle/disposal energy of the clamp with M/R is estimated to be only 9.9% and 8.1% respectively of that of the clamp without M/R. The results qualitatively demonstrate the benefits of M/R from the perspective of sustainability.

LCA together with the Embodied Energy metric proves to be of great value to overview a product's design from sourcing its materials through M/R to the its end-of-life. The energy for Phase 1 LCA is entirely input energy from, sourcing, design, manufacture and transport and can be efficiently recorded. The Phase 2 LCA presents a problem in that there is no recording of energy use or energy saving since the product is in the hands of the consumer. The maintenance component is the only component of Phase 2 LCA that can record energy usage and material/component flow into and out of the product.

The life evaluation of a component should be a calculated using predictive methodology or be derived from statistical data. Life evaluation based on pure judgment carries an element of risk. Combining these outcomes in the TDCMS, leads to a new maintenance approach, called sustainability centered maintenance (SCM)[1]. SCM is a comprehensive concept including the design and optimization of sustainability in the M/R process while MCSA is a sustainability analysis technique focused on the process. MCSA should be a useful tool to assist SCM procedure.

Maintenance procedures, often termed reliability centered maintenance (RCM), return the product to service for reliability and safety reasons. RCM is an isolated endeavour conducted without data feedback or recording of materials used or discarded. SCM benefits the current and future products by blending with RCM, thus becoming the data recording and material tracking facility, lacking in most RCM programs[12]. SCM feedbacks data to the design function and management and tracks components and materials for recycling and reuse, thus de-isolating the maintenance procedure and making data available to the entire life cycle management team. In this way an accurate EBS can be produced, providing a wealth of information. Efficient performance of LCA combined with SCM requires the TDCMS management overview to give a feedback of information from the product garnered from SCM[1].

SCM provides a means of reducing EE by data feedback and by applying recycling and reuse of materials and components, thus providing a major influence within the maintenance/refurbishment procedure. TDCMS and SCM integrated with MCSA becomes a central sustainability strategy to provide further information for enhancing the sustainability while reducing the life-cost of a product[3].

Abbreviations

EBS	Energy Balance Sheet
EE	Embodied Energy
EPS	Energy Primary Source
ISO	International Organization for Standardization
LCA	Life Cycle Analysis
M/R	Maintenance/Refurbishment
MCSA	Maintenance-Centered Sustainability Analysis
RCM	Reliability Centered Maintenance
SCM	Sustainability Centered Maintenance
SDV	Sustainability Disposal Value
TDCMS	Total Design Control Management Strategy
UL	Usage Life

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