# 11

# PURE: A Fuzzy Model for Product Upgradability and Reusability Evaluation for Remanufacture

Ke Xing, Kazem Abhary and Lee Luong

## 1. Introduction

Remanufacture strategy has been broadly applied to curb the environmental impacts of waste from discarded products. The strategy strives for waste reduction by promoting reutilisation and service life extension of end-of-life products. However, challenged by fast changing technologies and fashions, to rebuild a product just "as it is (or was)" often falls short in making it favourable in the market environment. It is important that the upgrade strategy can be incorporated with remanufacture to achieve a real effective reutilisation of products. In this paper, a mathematical model of product upgradability is proposed to measure a product's potential to accommodate incremental changes/improvements in its functionality during remanufacture. By using fuzzy set theory, the evaluation model represents and examines the product's fitness in terms of its technological, functional, physical, as well as structural characteristics, providing a number of indications for further improvement to base on.

### 1.1 Remanufacture and its Challenges

As a life cycle strategy supporting product service life extension, remanufacture has become a "rising giant" worldwide in recent years, providing very promising solutions to reduce the demands on landfill space and virgin materials through salvaging the reusable parts of retired products. It is regarded as the ultimate form of recycling as it recaptures the value-added to a product when it was first produced without reducing the product to its elemental form, e.g. materials or chemicals.

Generally, the physical as well as functional conditions of those end-of-life products are restored by rebuilding or replacing component parts wherever necessary and reassembling them to form "remanufactured products" (Rose

Source: Manufacturing the Future, Concepts - Technologies - Visions , ISBN 3-86611-198-3, pp. 908, ARS/plV, Germany, July 2006, Edited by: Kordic, V.; Lazinica, A. & Merdan, M.

2000; Ijomah et al. 1999). However, current trends of development in technologies and marketing present big challenges to the effectiveness of remanufacturing practice. The evolutionary changes to products often lead to higher market expectations on their functionality and make it more difficult for remanufactured products to be in line with the "like-new" criteria and customer demands. Also, the product variety generated by such changes and associated with customisation creates a new and more competitive arena for the remanufactured products to strive for their market status. In both circumstances, a conventional restoration of a product just "as it was" is becoming insufficient, sometimes even unworthy, to make it acceptable to the consumers. Therefore, a more ambitious upgrade strategy should be implemented in conjunction with remanufacture to champion its effectiveness and attractiveness.

### 1.2 Product Upgradability in the Context of Remanufacture

Different from the upgrade "on the drawing board" in the design phase, upgrading products through remanufacture is more based on the physical reuse of their current configurations. The improvement is added-in to the existing frames. During remanufacture, the intended changes to the existing physical configurations should be minimised, or even prohibited. Compared with the upgrading work in the design stage, there are more constraints and less freedom for incorporating new functions or improvements "off the drawing board" in the context of remanufacture. The most convenient as well as typical example of such upgrade is the plug-in feature of personal computers.

When a product life cycle process is analysed, the performance or potential of this practice is addressed and measured in terms of its "*-ability*", which stands for the characteristics, or the virtue, of the process (Huang 1996). Upgrade is one of the elements of product life cycle processes. Therefore, following the pattern of "*x-ability*", in its simplified form product *upgradability* can be defined as the level of potential of a product to be effectively as well as efficiently upgraded.

Given the commonalities and, more importantly, the differences of product upgrade in the two circumstances, the upgradability of a product in remanufacture can be regarded as a reflection of its characteristics supporting new functions or improvement and reuse at the engineering metrics level, the component level, and the structure level, featuring the projections from customer demands to the different hierarchies of domains for the configuration of products.

Generically, the fitness of engineering metrics settings to upgrade is represented by the compatibility of the current parameters to the new functions or improvements. At the component level, whether the product is upgradable in the context remanufacture is influenced by the reusability of the components. Understandably, unless the key components are reusable for an extended service life, the product is not worth to be remanufactured and thus unsupportive for upgrading. A modular structure is ideal for ease of swap and upgrade during remanufacturing processes. Therefore, at the structure level, the upgradability of a product can be addressed in terms of its modularity feature. From this perspective, the upgradability of a product in the context of remanufacture is represented in the form of a system of characteristics from different levels. It is a joint effect, or integration, of parametrical compatibility, component reusability and structural modularity.

### 1.3 Current Works on Product Upgradability and Limitations

The incorporation of refurbishments and technical upgrades is regarded as a resources and energy efficient way to achieve product life cycle extension in remanufacturing environment (Guide & Srivastava 1997). As a form of retrofitting, upgrading products in association with remanufacture in various industry contexts has been quite extensively researched, ranging from the improvement of productive life of injection moulding machines (Overfield 1979), the rebuild of used machine tools for performance (Drozda 1984) and the renewal of power generation equipment (Beck & Gros 1997), to the rotorcraft modernisation for US Marine Corps (Wall 2004). In these works, upgrade opportunity of the products was studied as the complements to where remanufacture alone fell short to provide holistic solutions. However, the investigations in those works were mainly focused on operational issues rather than studying the inherent ease-of-upgrade characteristics of the products.

The major aims of assessing product upgradability are to make a long-term upgrade plan for multi-generations of a product during its use or remanufacturing stage and assist designers to derive a suitable design solution to for the whole product (Umemori et al. 2001). The effects of structural configuration on system upgradability was studied by Pridmore et al. (1997) when they investigated the favourable configuration forms for rapid prototyping of application-specific signal processor, which enable both hardware and software reuse with open interface standards. The techno-financial dominance of upgrade option was highlighted in work of Wilhelm et al. (2003) through emphasizing the content and timing of upgrades in maximising the life cycle revenue of a family of high-tech products. Shimomura and the colleagues (1999) stressed the significance of a product's upgradability to the extension of its service life and the reduction of resource and energy consumption. By comparing upgradable artefacts and design with traditional modes, they proposed two basic guiding principles for improving product upgradability, namely "function independent" and "function insensitive". Umeda and his team furthered the research and implemented the two principles as the basis to analyse the linkage between function parameters and design parameters, represented as a casual relation graph, and evaluate the upgrade potential of products (Umemori et al. 2001; Ishigami et al. 2003)

Nevertheless, the reviews on the features of contemporary works show that the synergy of technology improvement, module introduction, system reliability and component reusability is not sufficiently reflected by the current representations and measures of products' potential for upgrade. The works focusing on the modelling of product upgradability are scars and there is lack of a systematic way to incorporate the key technical factors from the three major product domains in the formulation of upgradability evaluation approaches.

In order to overcome the limitations of the current research and methods, this paper is to propose an integrated evaluation approach for a product's upgrade potential, Product Upgradability and Reusability Evaluator (PURE), with an integral consideration of the fitness of its functional, physical and structural characteristics, and the ability to identify the weaknesses in its configurations for improvement. The implementation of this approach is intended to incorporate with the design of products to represent and measure their upgradability, identifying the weaknesses in their configurations for design improvement.

In the subsequent arrangement of the paper, Section 2 is dedicated to propose three key technical indicators to represent and measure the upgradability features of products. Following that, the approach of PURE is elaborated in Section 3 with the formulation of mathematical models for product upgradability and its indicators by using Fuzzy Set Theory. Then, in Section 4, a case study on a Solar Roof Home Heating System is provided to demonstrate its effectiveness in evaluating product upgradability for different upgrade scenarios. Finally, the features of this upgradability evaluation approach and the future work will be discussed in the summary.

## 2. Upgradability Indicators of PURE

As discussed in the previous section, in the context of remanufacture product upgradability is regarded as an integrated reflection of the characteristics of being compatible in functional parameters, containing reusable "core" (key components), and having a modular structure. In the approach of PURE, three technical factors are defined as the indicators for the corresponding characteristics, and they are adopted for the measure of a product's suitability to upgrade.

### 2.1 Indicator of Compatibility to Generational Variety (CGV)

Generally, generational variety is created through introducing a variety of evolutionary changes or incremental improvements to the functionality of a product on the base of the existing settings. As far as product upgradability be concerned, when the new functions or improvements are mapped as customer requirements to corresponding engineering metrics (EM) of product functions in the functional domain, it is important that the current parameters of those EMs have certain levels of fitness to meet the new requirements and ability to accommodate the changes. For any individual metric, its susceptibility to the direct or indirect impacts of upgrade rests with the conformance of its parametrical setting with the possible new performance requirement imposed on it by the functionality improvement. Practically, the smaller the gap between the current performance and the new ideal performance of an engineering metric, the higher the contribution it has to the ease-of-upgrade potential of the product. By forecasting the possible functional changes and their effects on the EMs of the product, such fitness can be represented and measured as the reflection of the degrees of disagreement, or distance, between the current and the expected EM values.

An indicator of Compatibility to Generational Variety (CGV) is proposed and used in this approach to signify and assess the fitness of EMs and their current valuation to the ease-of-upgrade potential of products in the functional domain. It intends to reveal whether and how much the present metrical settings of interest are parametrically in tune with the performance requirements imposed on them in the upgraded model. By using CGV to represent and measure the fitness of a given engineering metric, it is capable of reflecting:

1. the suitability of this engineering metric for being a core metric,

2. the fitness of the current parametrical setting to serve the product platform for generational variety, and
3. the level of difficulty to configure this engineering metric as a core metric of product platform and its impact to the product's upgradability.

For an EM, the higher the value of its CGV, the less sensitive it might become in facing the changes of functions.

### 2.2 Indicator of Fitness to Extended Utilisation (FEU)

For remanufacture and upgrade, the "core" of a product consists of the valuable components that perform the enabling functions. In the given context, a crucial trait of those core components to support the ease-of-upgrade potential is their fitness to serve an extended use life. For components in the physical domain, this fitness represents the level of reusability, which is inherently constrained by the functional and the physical states. By studying the correlation between product upgradability and product reusability, it is logical to assert that being able to reuse is a necessary condition for a product's upgradability. After all, any upgrade option applied to a product is to enable it to serve longer with better and/or more functions. A product's reuse potential is defined by the states of its functional components.

In the PURE, an indicator of Fitness to Extended Utilisation (FEU) is designed to feature and measure the reusability of components and the product that they reside in. The factor of FEU can be defined as the integration of the effects of functional reusability (FRe) and physical reusability (PRe). For a component, its functional reusability (FRe) represents the technological fitness to service life extension, or in other words the potential of remaining functionally and technologically conform with the expectation of users after a period of use time.

By focusing on essentiality, the key factors contributing to components' FRe state are their technological maturity features, functional performance features, and design cycles. The PRe value of a component is featured as the reflection of its physical condition to serve an extended use life. After serving a certain period of time, this fitness represents the chance of performing the intended function satisfactorily for another unit of time under the specified conditions. Hence, PRe is inherently time-dependent and associated with the level of reliability (R) and the failure rate of components.

## 2.3 Indicator of Life-cycle Oriented Modularity (LOM)

Intrinsically, the architectural complexity of a product is influenced by states of the links or relationships among its components. Modularisation is an effective way of integrating manifold component relationships to simplify the structural configuration of products, facilitating multiple life-cycle processes and their virtues. A modular product serves a common interest of upgrade and remanufacture by facilitating the separation, swap and insertion of interested components. The modularity of a product is an indication of the degrees of intra-module correlations and inter-module dependence in its structural configuration. These two features are represented in the forms of Correspondence Ratio (CR) and Cluster Independence Index (CI) (Newcomb et al. 1998; Hata et al. 2001).

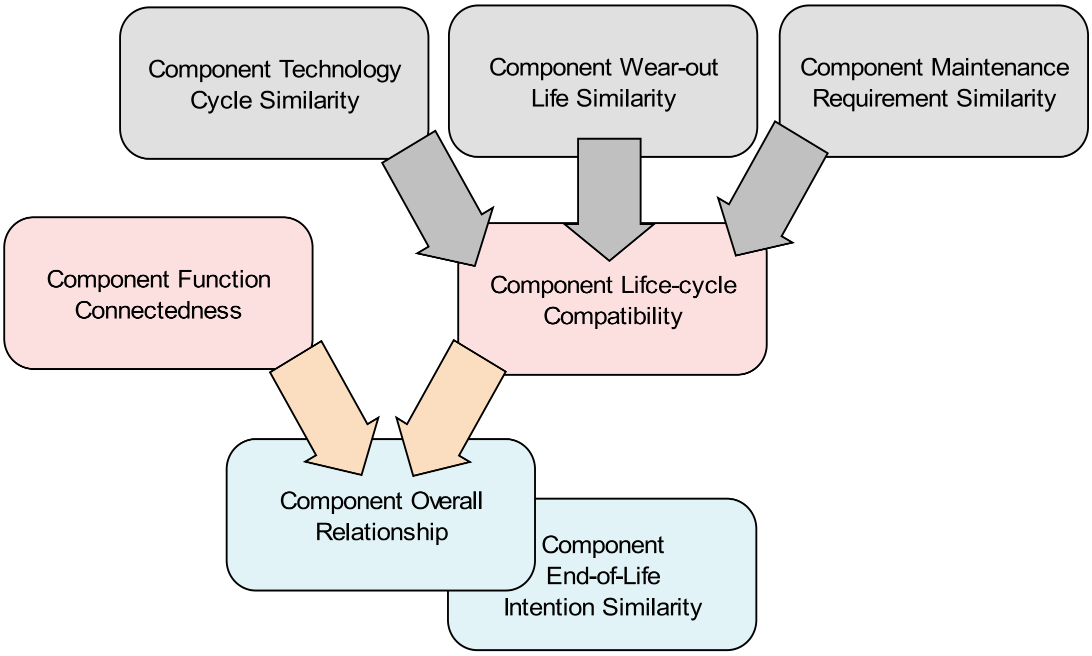


Figure 1. A Hierarchy of Component Relationships

Accordingly, the indicator of Life-Cycle Oriented Modularity (LOM) is introduced to provide a comprehensive vision and address the life cycle concerns that are influential to both upgrade and remanufacture in the measure of the two indexes and product modularity. CR measures the strength of connections among the components within a module. Components having similar life cycle features (e.g. technological life, physical life, service requirements, etc.) and strong functional connectivity (in terms of material, signal, and energy flows) often tend to have similar end-of-life paths. Therefore, a set of component relationships (Figure 1) proposed by the authors (Xing 2003) is used to evaluate the CR value of each module formed in the product. For CI, the focal point of evaluation is at the physical links among the components of a module in comparison with the total links to the module, which suggests the potential complexity and amount of required effort involved in upgrade and remanufacturing operations.

## 3. Models and Evaluation Mechanism of PURE

Implemented in the remanufacture context, the approach of PURE is a formulated mathematical model that aims at assessing the potential of a product to be upgraded and reused contributing to its service life extension through remanufacturing operations.

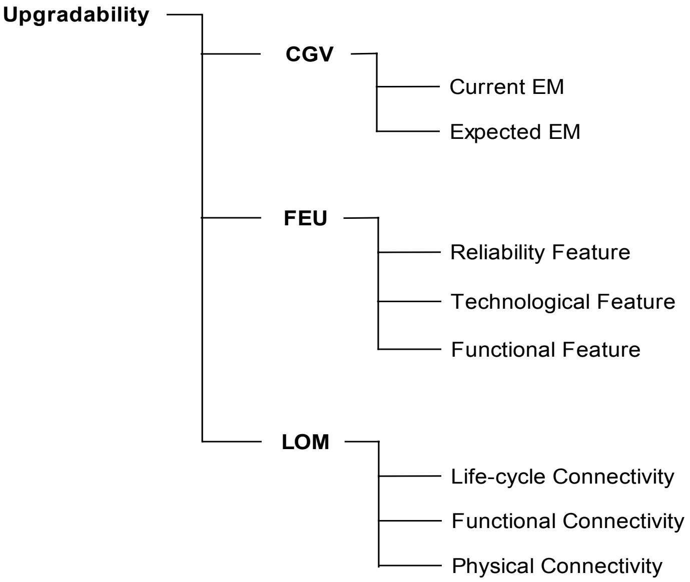


Figure 2. Scope of Product Upgradability and Its Indicators

Suggested by the name of the approach, the introduction of the featuring indicators of ease-of-upgrade characteristics and the modelling of product upgradability are conducted on the basis of the inherent connections and commonalities of product upgradability and product reusability.

In the last section, three featuring indicators for product upgradability are defined and discussed. Each of them is corresponding to a particular style of product representation and addresses one major characteristic pertinent to products' upgrade and reutilisation potential. Together, CGV, FEU and LOM contribute to the overall upgradability level of a product. The figure below (Figure 2) provides an overview of product upgradability, upgradability indicators and the associated factors.

### 3.1 Fuzzy Nature of Product Upgradability Representation and Evaluation

In this work, the product upgradability issue is studied in the context of remanufacture, which is featured by product life-cycle characteristics, and the PURE approach is to incorporate with product design for upgradability improvement. Therefore, the initiation of product upgradability evaluation is inevitably coupled with the inherent uncertainties residing in the collection and interpretation of product life-cycle information in the early phase of product development. Essentially, the sources of those uncertainties are the qualitative descriptions of pertinent product characteristics, the subjectivity of decision-making based on expertise and empirical experience, the lack of accurate design data and product life cycle information, and the design factors that are usually not within the control of designers (Wang *et al.*, 1999; Xing *et al.*, 2002).

The same situation exists for the identifications of upgrade opportunities and scenarios. The technological evolution characteristics of the product, the possible changes in customer expectations, and the compatibility of components to the changes are examined for the prediction of progressive changes in a product's functionality. Given the fact that in general those design information are expertise-based, qualitatively expressed and subjectively assessed, the phenomenon of fuzziness exists and it is largely a matter of degrees of belief regarding to what, when and how the functional changes or improvements will happen and their impacts to the product's function system. Furthermore, in the design of a product, the configuration of the product's structure, where modularity is usually a preferred feature to achieve, is based on examining the interactions among the components in abstract forms of semantic links, such as containment, alignment, affiliation, etc. (Ishii 1994; de Souza *et al.*, 1996). Under the circumstances of remanufacture and upgrade, the implications of life cycle characteristics in product upgradability considerations introduce extra dimensions into the relationships of components in addition to their physical links, geometrical interactions and functional connections. Linguistic values, such as very strong/high, strong/high, medium, weak/low and very weak/low, are usually applied to represent the levels of similarity, connectivity or compatibility among its components, which are very difficult to be depicted in a binary way. Intrinsically, these qualitatively classified (i.e. highly related or moderately related) and often subjectively valued (i.e. five-category score assignment) attributes exhibit the very characteristic of fuzziness and are of fuzzy concept (Li *et al.*, 2000).

Fuzzy set theory is firstly introduced by Zadeh (1965) and fuzzy approaches have been effectively used to solve the vagueness or fuzziness in uncertain information, subjective decision-making and multi-attribute related problems. As a powerful mathematic tool, the advantage of applying fuzzy set theory in tackling product upgradability representation and evaluation problems, which have fuzzy features implicated, is significant and promising. To the design practices for upgradability associated with reuse or remanufacture, fuzzy set theory can have its major contributions in the aspects:

1. the assessment of the fitness of a product to remanufacture and functionality improvement,
2. component categorisation and clustering for efficient maintenance or replacement based on the similarity or compatibility of their characteristics, and
3. the evaluation of component life cycle interconnections in the forms of semantic linkage or design alternatives with regard to the given linguistic measures.

Therefore, two of the major elements of fuzzy set theory hereby present themselves as very useful tools for the above-mentioned tasks – *fuzzy membership values and functions* and *fuzzy relationships*. In PURE, they are used to formulate the mathematical models for the key characteristics of product upgradability.

### 3.2 Basic Notions for Product Upgradability Evaluation

Although the implication of cost concerns and the impacts of economic factors are critical in determining the viability of end-of-life options of products, the emphasis on their roles could be easily taken with bias over the exploration on other essential life cycle factors and the technical solutions for their improvement. As upgradability is regarded as an intrinsic virtue of a product, the formulation of the PURE model in this work is based on the key technical factors that contribute to the ease-of-upgrade characteristics of a product.

Essentially, the suitability of a product to upgrade in the event of remanufacture is dependent of its type, mode of upgrade, and structural as well as physical features. In this work, the focus of interest is set on electr(on)ic products and electro-mechanical equipment which are most frequently treated in remanufacturing practice and generally more amiable to upgrade. Furthermore, the context of remanufacture in which product upgradability is concerned dictates that the functionality upgrade considered in this work are achieved through improving the hardware (e.g. adding or replacing parts, modules or subassemblies) rather than the software of a product. Considering the features and requirements of remanufacture and hardware upgrade, the product undergone the processes has to be structurally separable and physically serviceable. Such characteristics suggest that the product of interest should be a durable multi-component system and can be repaired once failures have occurred. Non-destructive separation of components is imperative to upgrade and remanufacture purposes. In accordance with the discussions above, following basic conditions are further assumed as the basis for the modelling and measure of product upgradability:

- *Assumption 1*: Products or systems considered in this work are reparable electro-mechanical products or systems working in normal conditions with standard usage, which exclude the impacts exerted by any external abnormalities, such as abuse and unforeseeable changes of the ambient environment,
- *Assumption 2*: Components examined in this work are the functional parts of a product or system. Connective parts, such as fasteners, cables, wires, harness, etc., are left out of the consideration to minimise distraction in that they normally have very long physical as well as technological life, but little functional importance to upgrade,
- *Assumption 3*: The fitness of an engineering metrics or a component in respect of any given upgrade option and reutilisation strategy is considered as independent of the conditions of other engineering metrics or components in the product, which is to simplify the complexity of the study, concentrate the examination on the essential factors of components, and model

upgradability truly on the basis of the inherent characteristics of each individual element of product representations.

- Assumption 4: A product is regarded as upgradable if its level of upgradability is higher than a threshold value that can be set by designers or companies. In this case, the qualitative concept of upgradability can be translated as a measurable indication based on expertise, facilitating the interpretation of the status of "being upgradable".

## 3.3 Formulation of PURE

Although a virtue of intrinsic characteristic, the upgradability of a product is in fact quite conditional and closely associated with the time constraint and the functional changes to apply. To ensure the success of the evaluation of a product's ease-of-upgrade potential, a prerequisite is to analyse the targeted product regarding to its functional and life cycle features. Considering technological, functional, physical, and time implications in upgrade and remanufacture, it is essential to facilitate the upgradability evaluation by identifying the following basic information:

1. The product function system, its key components and interconnections among the components,
2. The technical characteristics of the product and its components,
3. The time frame, or the planning horizon, for the upgrade and remanufacture considerations, and
4. The number and types of possible incremental changes or improvements to be applied to the functionality of the product within the defined time frame.

Based on the information above, the formulation of the PURE to assess product upgrade potential takes the steps to construct the mathematical models for the key indicators and the overall upgradability.

### 3.3.1 Modelling and Measure of CGV

The generic mappings among the domains of customer requirements, engineering metrics, and components are depicted in the form as Figure 3 and facilitated by implementing QFD. Therefore, a product system can be represented a set $\Upsilon(r_1, r_2, \ldots, r_m)$, where $r_i$ is an engineering metric of the functions of the product and m (≥1) stands for the number of engineering metrics.

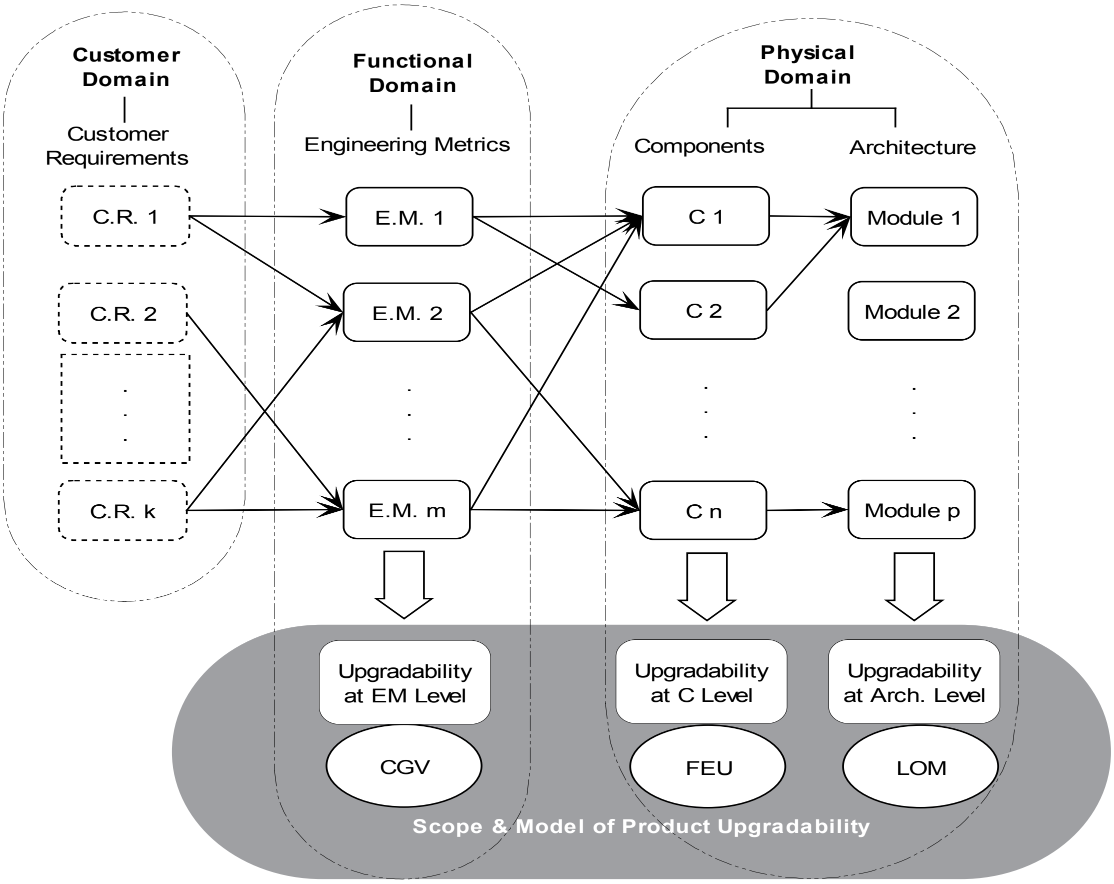


Figure 3. Mappings among the Design Domains for Product Upgradability Representation

For each engineering metric $r_i$ (i = 1,2, …, m), it is regarded a function of a number of corresponding components composing a subset of $C(c_1, c_2, \ldots, c_n)$ (n≥1), which is expressed as

$$r_i = g(\{c\}), \quad \{c\} \subseteq C \tag{1}$$

With the introduction of generational changes, often a new performance requirement on any an existing engineering metric $r_i$ ($r_i \in \Upsilon$) is expected. Exhibiting the same feature, this engineering metric of the new generation product is denoted as $r_i^e$. Assuming that $r_i^e$ is always not worse than $r_i$ in terms of functionality, the state of the current $r_i$ to the change, CGV$_i$, is measured as a membership value of fitness by the following fuzzy membership function and illustrated as Figure 3. The coefficient $\tau$ is a vector of the standard gradient of improvement for a given EM. A positive $\tau$ designates the improvement of "increasing" the current value, while a negative $\tau$ stands for the opposite direction. The coefficient $\kappa$ valued as 0.1, 0.3, 0.5, 0.7, or 0.9 represents the ascending level of difficulty or significance of the improvement.

$$CGV_i = \exp\left[-\kappa\left(\frac{\gamma_i^e - \gamma_i}{\tau}\right)\right] \tag{2}$$

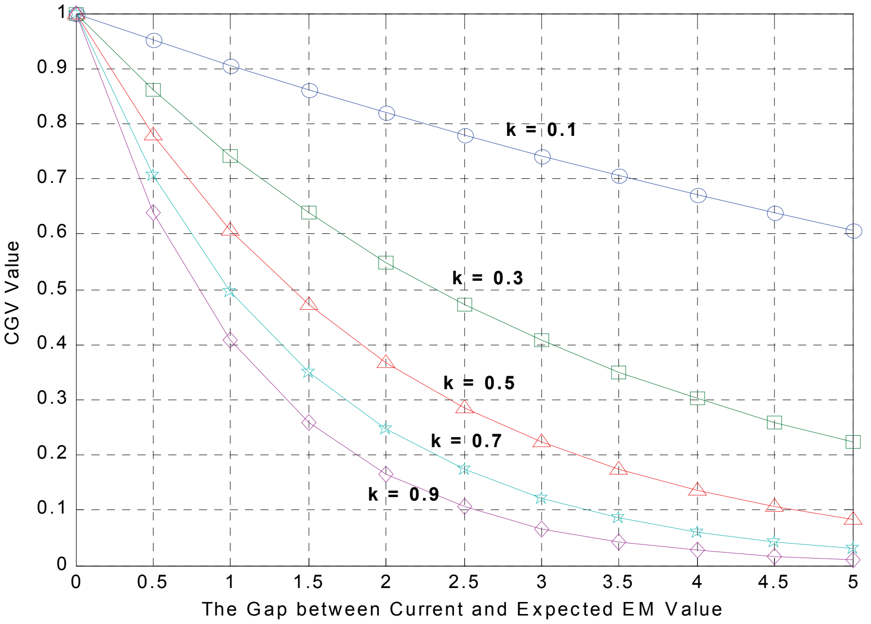


Figure 4. Function of CGV ($\tau = 2$)

Given the different importance of engineering metrics to the functionality of a product, the overall CGV at the system level, CGV$_{sys}$, is modelled as the aggregation of the weighted CGV of all the *r*s of $\Upsilon$. The assignment of weight to engineering metrics is conducted on the basis of function analysis and their correspondence to the fulfilment of the identified customer requirements. Metrics corresponding to functions that address important customer requirements should be given higher values of weight for their impacts on the shape-up of CGV$_{sys}$.

$$CGV_{sys} = \sum_{i=1}^{m} w_i CGV_i \text{ where } w_i \text{ is the weight of } r_i \text{ and } \sum w_i = 1 \quad (3)$$

According to the ways that CGV$_i$ and CGV$_{sys}$ are measured, the more engineering metrics of a product affected by functional changes during upgrade, the lower the level of $CGV_{sys}$ will become and the more difficult for the product to be upgraded. If a product is highly specified or compactly designed, any changes introduced to the functionality of the product by an upgrade plan could affect the whole system of engineering metrics. In such circumstances, many of the engineering metrics would have the "expected values" identified as being significantly different from their current parametrical settings. It suggests that a great deal of effort might be needed to bridge such "gaps" between the two sets of values. Consequently, the CGV value of the product and its potential to upgrade will become much lower than the designs that are less specified or compact.

### 3.3.2 Modelling and Measure of FEU

In the event of remanufacture and upgrade, the suitability of a component to reuse is measured as functional reusability (FRe) and physical reusability (PRe). For any component $c_i$ ($c_i \in C$, i = 1, 2, …, n), FRe$_i$ and PRe$_i$ are described by the grades of their membership values to the states of being "desirable" and "reliable" after serving a certain period of time $t$ under the specified conditions. Regarding to the status of "being reusable", the membership degree quantifying the PRe level of a component is computed against the specified boundary values of reliability, usually standing for the minimum expected and the ideal reliability state. If an exponential feature and a constant instantaneous failure rate are assumed, for any a component $c_i$ its $PRe_i(t)$ can be expressed as Eq.4 where $\lambda_i$ is the instantaneous failure rate and $R_{\min}$ is the minimum expected reliability.

$$PRe_i(t) = \frac{\max\left[0, (e^{-\lambda_i t} - R_{\min})\right]}{1 - R_{\min}} \quad (4)$$

A practical way to define the $R^{\min}$ value for each component is through reliability allocation at the component level of product representation. Usually, the minimum reliability is much more obvious and easier to specify at the system level. After setting the $R^{min}$ of the system, the corresponding minimum acceptable reliability of each subsystem or component in the system can be identified through the analysis of the hierarchy of the system representation and the reliability block diagram which demonstrates the configuration of the product function system. A methodical process of top-down allocation of reliability through the systems hierarchy is detailed in the ref. (Blanchard et al. 1995).

As component desirability is a very subjective and fuzzy concept, it is difficult to have a direct quantitative measure of desirability level and FRe. Nevertheless, given the associations between the length of technology cycle (TC), the maturity of technology, and the suitability for reutilisation, to use the membership degree of TC to the concept of "being long" to represent the status of "being desirable" becomes a quite reasonable option. It is suggested that the maximum TC of "New Economy/I.T. " products is 5.5 years (Rose 2000). Based on this, 5.5-year life is used as the empirical rough pre-evaluation standard for the fast classification such as "rather short" or "rather long". A Sigmoid-Shape membership function is adopted for the evaluation. Expressed as the probability of not being obsolescent by time $t$ and assumed to exhibit an exponential feature, the $FRe_i(t)$ of component $c_i$ is defined as Eq.5

$$FRe_i(t) = \frac{1}{1 + \exp\left[-0.5 * \left(ETL_i(t) - 5.5\right)\right]}, \quad i = 1, 2, \ldots, n \qquad (5)$$

$ETL_i$ is the effective technology life of component $c_i$. For a component, its ETL is equivalent to its theoretical technology life – $TC$ when the component is unrivalled or at the start of its service ($t \le$ DC). ETL degrades along with time when more new designs are introduced ($t >$ DC).

| **Linguistic Values** | **Scores** |
|---|---|
| Very High | 0.90 ~ 1.00 |
| High | 0.70 ~ 0.89 |
| Medium | 0.50 ~ 0.69 |
| Low | 0.30 ~ 0.49 |
| Very Low | 0.00 ~ 0.29 |

Table 1. Measure and value range of FL

Given the fact that components using the same technology have different performance levels and usually the one with better performance serves longer, the pace of degradation of a component's ETL is dictated by its functionality level (FL) which denotes the quality to function in comparison with the industry benchmarks or the best design in the market (Table 1).

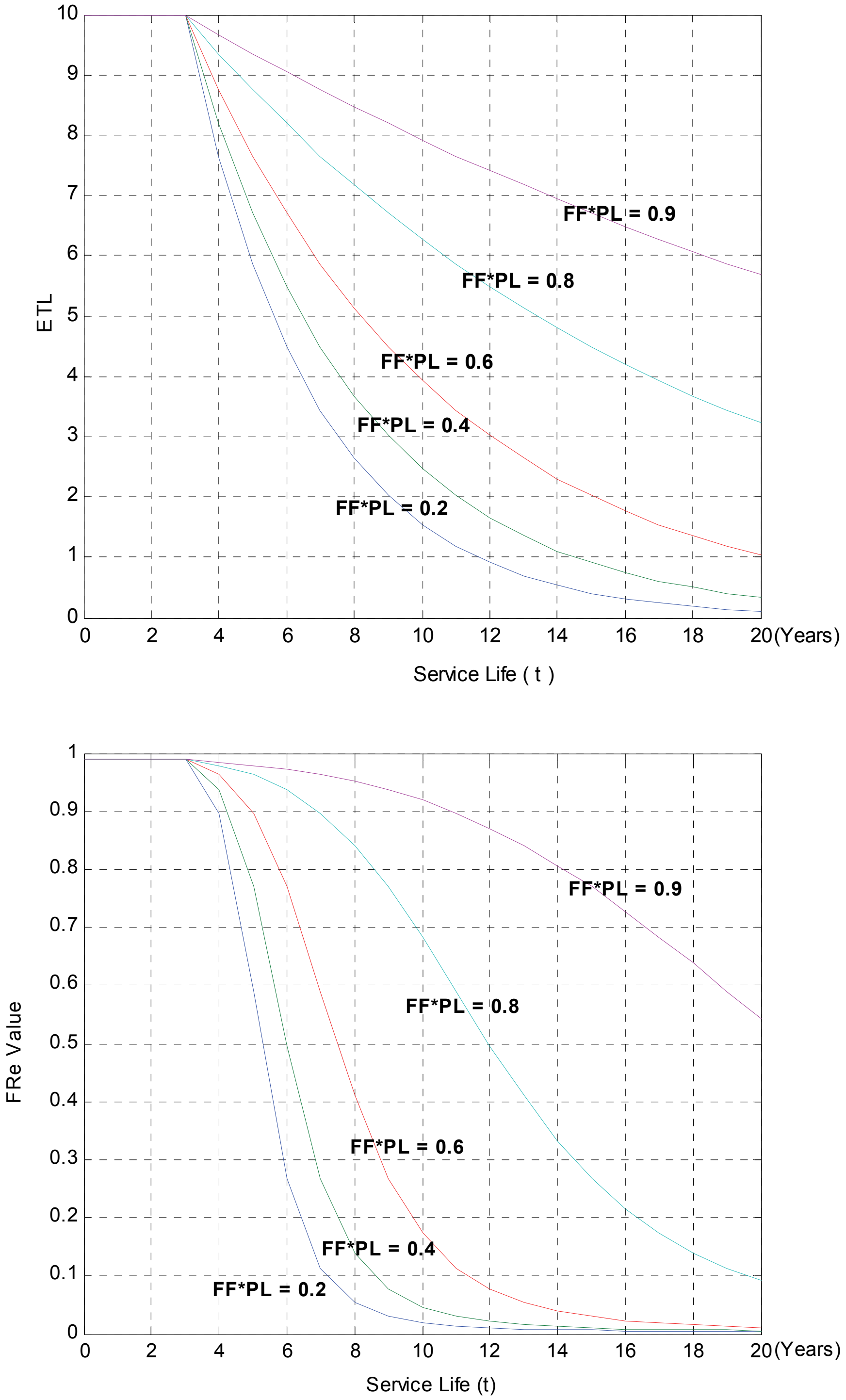
Consequently, ETL can be considered as a function of TC, DC, FL, and the time factor $t$ (Figure 5). By assuming an exponential mode for the degradation of ETL, for any component $c_i$, the function of its ETL is expressed as Eq.6.

$$ETL_i(t) = TC_i \exp\left[ -(1 - FL_i) * \max\left[ 0, \left( \frac{t}{DC_i} - 1 \right) \right] \right], \ i = 1, 2, , n \qquad (6)$$

The formation of FEU model is based on the integration of the model of PRe and the model of FRe. In the circumstances of remanufacture, the "shorter plank" of FRe and PRe plays a crucial role in determining the fitness of components to serve. While, the other one provides a strengthening effect which could help to enhance the chance of reutilisation, but will not dramatically improve component reusability. Therefore, at the moment of $t$ the FEU of component $c_i$ (i = 1, 2, …, n) is measured by Eq.7 and the reusability of the entire system is represented in the form of Eq.8. Apparently, the more important a component is, the greater the impact that it exerts on the FEU value of the product, which is in accordance with the notion of the role of key components. As assumed, only key and auxiliary components are considered in the product representation and the modelling. The contributions of the components to the ultimate reusability at the system level, $FEU_{sys}$, are directly related with their importance to the functionality of the product, which can be identified through the mappings among customer requirements, engineering metrics and components.

$$FEU_i = \min\left[ FRe , PRe_i \right]^{\left( 1 - \frac{\max\left[ FRe_i \ PRe_i \right]}{2} \right)}, \ i = 1, 2, , n \qquad (7)$$

$$FEU_{sys} = \sum_{i=1}^{n} w_i FEU_i , \quad \sum_{i=1}^{n} w_i = 1 \qquad (8)$$



ETL-function FRe-function

Figure 5. Functions of ETL and FRe (TC=10; DC= 3)

### *3.3.3 Modelling and Measure of LOM*

As described in previous sections, the modularity of a product is assessed Correspondence Ration (CR) and Cluster Index (CI). If the product consists of M modules, for each individual module its CR level is determined by the intensity of the interconnections among the constituent components, and its CI level is an indication of physical independence from the other modules. The states of components' interconnections are determined by their functionality connectedness and similarities in technological life, physical life, and service requirements, which are intrinsically of fuzzy nature. The overall relationship among the components in the same module, denoted as $\tilde{R}$, is measured as the basis for the evaluation of CR level of the module. The evaluations of those fuzzy component relationships in the context of remanufacture are elaborated in detail in the ref. (Xing et al. 2003). For any module $m_i$ ($i$ = 1, 2, …, M) with $p$ components, the indicator of $CR_i$ is calculated as:

$$CR_i = \begin{cases} 1 & , \quad if \quad p = 1 \\ \dfrac{\sum\limits_{k=1} \sum\limits_{l=1} \tilde{R}(k,l)}{p(p-1)/2} & , \quad otherwise \end{cases} \tag{9}$$

The level of CI level is very critical to the level of difficulty and the operational effort of product reprocessing in the context of remanufacture. Remanufacture is featured by a complete disassembly of a large quantity of products. The investigation on the empirical data from disassembled products with more than one module shows that the interaction metric of a module becomes high or very high when its inter-module physical links are approximately 3 or greater (Allen & Calson-Skalak, 1998). Therefore, the value of 3 is used as a reference value to measure the membership of the inter-module links of a module to the concept of "having high interaction metric", featured by Eq.10, where the value of -2 is adopted to ensure that the interaction metric is close to zero when inter-module links approach zero. By incorporating the consideration of module interaction metric into the measure of module independence, the CI value of module $m_i$ is calculated by using Eq.11.

$$\alpha_i = \frac{1}{1 + \exp\left[-2 * \left(LINKS_i^{Inter-module} - 3\right)\right]} \quad , \quad i = 1, 2, \ldots, M \tag{10}$$

$$CI_i = 1 - \left( \frac{LINKS_i^{Inter-module}}{LINKS_i^{Total}} \right) * \alpha_i \tag{11}$$

According the equations above, by reducing the constituent components in each module, the number of modules in the product is increased and in turn the CR values of individual modules could be improved. However, a most probable adverse effect resulted from such change would be the decrease of the number of intra-module physical links in the total number of links and thus a lower CI value for each module. Upgrade through remanufacture is often conducted in a mass production scale. All the modules are disconnected from each other and treated before being recombined with new components. The CI status of the product directly reflects the fitness of its structural configuration to meet the requirements of remanufacture. Having less modules and weak inter-module links is highly important to the interest of product upgradability in this particular context. Relatively, CR is less important in such circumstances. The increase of module quantity associated with a larger CR is not in favour of remanufacturing operations. Consequently, LOM is formulated as Eq.12, where 0.5 is the theoretical maximum weight of importance.

$$LOM = \left( \frac{\sum_{i=1}^{M} CI_i}{M} \right)^{\left( 1 - 0.5 * \frac{\sum_{i=1}^{M} CR_i}{M} \right)} \tag{12}$$

### 3.3.4 Modelling and Measure of Product Upgradability

After modelling the three characteristics, the upgradability index of a product (PUI) is measured as a function of CGV, FEU and LOM. As a tripod stool that is usually crippled by its shortest leg, the overall upgradability of a product supported by three ease-of-upgrade characteristics is to a large extent determined by the "weakest link" of them. Eq.12 below presents the formulation of the mathematical expression of PUI.

$$PUI = \min\left[CGV_{sys}\ ,\ FEU_{sys}\ ,\ LOM_{sys}\right]^{\left[1-\frac{h}{3}\right]} \qquad (12)$$

$$\left(CGV_{sys} + FEU_{sys} + LOM_{sys}\right) - \min\left[CGV_{sys},\ FEU_{sys}\ ,\ LOM_{sys}\right]$$

The success of the PURE relies on its ability to identify the inherent fitness of a product to the given upgrade scenario, consisting of a plan for functional improvement and the timeframe (planning horizon) for the implementation of intended upgrade. The upgradability evaluation results from the PURE model should be able to provide users informative indications for any redesign or reconfiguration of the product for ease-of-upgrade features of to base on.

## 4. Case Study

In this case example, the application of PURE on a Roof-Integrated Solar Air Heating System (RISAHS) is analysed. This technology is being developed by the Sustainable Energy Centre at the University of South Australia. The RISAHS utilises solar energy to provide space heating for a building. As with traditional solar air heating systems a *collector* is required to absorb the solar energy and is used to heat air. This air is distributed throughout the building via a *fan* and *ducting*.

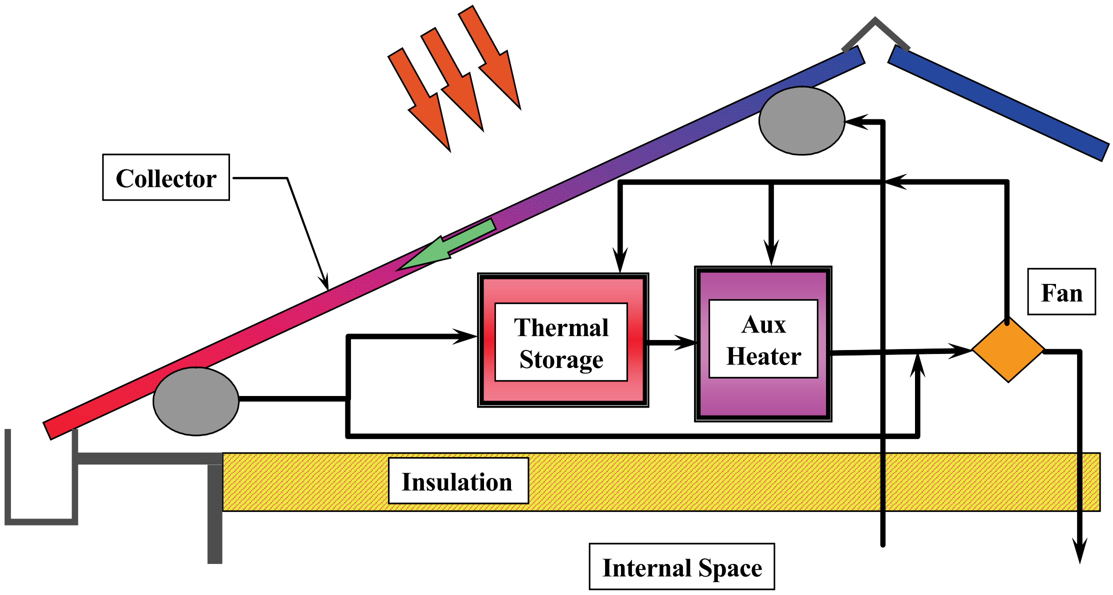


Figure 6. A Schematic View of Roof Integrated Solar Air Heating System

The collector can provide heating when there is a high level of sunshine. A *thermal storage unit* (TSU), which is charged by the collector, is used to store heat for times when there is inadequate levels of sunshine, and is charged by the collector. For times when the storage facility is empty, an *auxiliary backup heater* is used (Belusko et al. 2004). A *control panel* with a control system is integrated into the system to control the different heating operations of the system. The schematic representation of the RISAHS is shown as Figure 6.
The upgrade plan applicable to the system is assumed in the context of remanufacture. Table 2 presents the basic information of the engineering metrics and their current as well as expected values.

| Code | Engineering Metrics | Unit | Weight | Current Value | Expected Value | $\tau$ | $\kappa$ |
|---|---|---|---|---|---|---|---|
| EM1 | Average temperature | deg.C | 0.31 | 2 | 0 | -1.75 | 0.3 |
| EM2 | Volume of outside air | air changes/day | 0.08 | 3.75 | 15 | 7.5 | 0.1 |
| EM3 | System min. heating capacity/heating load | kw/kw | 0.17 | 0.75 | 0.9 | 0.2 | 0.3 |
| EM4 | Max. room temp. - Min. room temp. | deg.C | 0.06 | 2 | 1 | -1 | 0.1 |
| EM5 | Max air velocity at head height | m/s | 0.08 | 0.5 | 0.25 | -0.325 | 0.1 |
| EM6 | Solar heating/total heating | MJ/MJ | 0.10 | 0.45 | 0.7 | 0.2 | 0.5 |
| EM7 | The conventional energy use | MJ/m2 | 0.10 | 20.6 | 13.7 | -4.3 | 0.5 |
| EM8 | Amount of CO2 produced | kg/m2 | 0.10 | 9.8 | 0.1 | -2.3 | 0.5 |

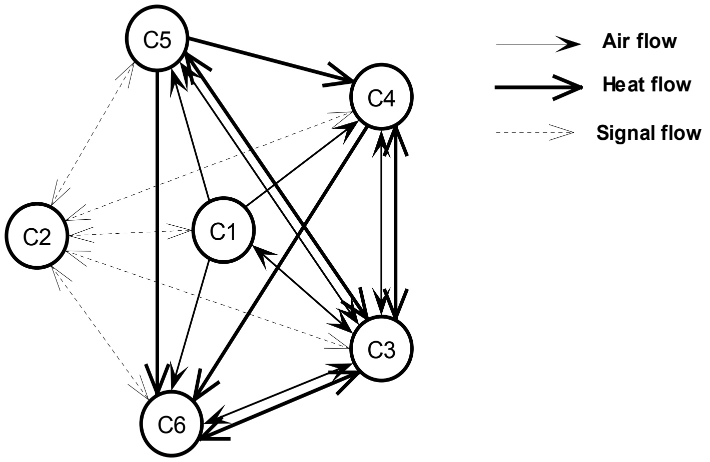
Table 2. Engineering metrics information of the RISAHS

As described above, there are six major functional components in this RISAHS, having different operation time per annum. In this case study, we assume that 1) the planning horizon for the upgrade consideration is 5 years, and the minimum acceptable level of reliability for the components in the system at any time is 0.3. The information about the importance rankings, technological life, physical life and reliability feature of the components are listed in Table 3.

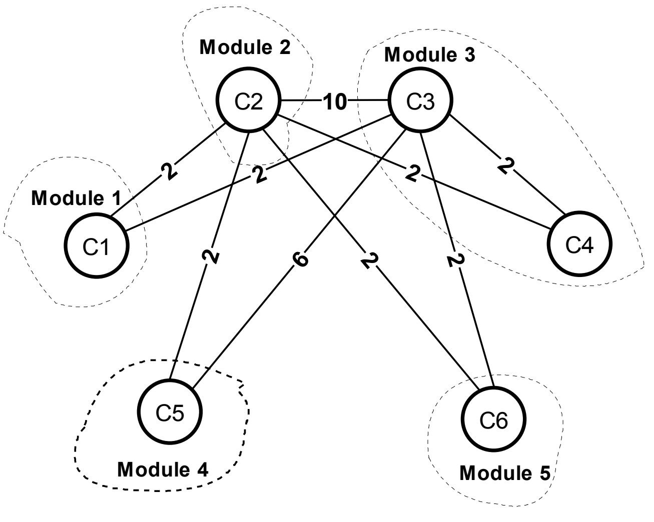
| Code | Component | Weight | Technology Life (yr) | Design Cycle (yr) | Functionality Level | Physical Life | Failure Rate | Working Hours/yr |
|---|---|---|---|---|---|---|---|---|
| C1 | Fan | 0.1 | 13 | 5 | 0.65 | 15 | 0.00001 | 2361 |
| C2 | Controls | 0.1 | 3 | 2 | 0.55 | 15 | 0.000001 | 2361 |
| C3 | Ducting | 0.05 | 15 | 7 | 0.75 | 15 | 0.00002 | 2361 |
| C4 | TSU | 0.25 | 8 | 5 | 0.35 | 15 | 0.00001 | 1458 |
| C5 | Collector | 0.35 | 8 | 5 | 0.4 | 15 | 0.00001 | 1180 |
| C6 | Aux. Heater | 0.15 | 10 | 5 | 0.8 | 15 | 0.00001 | 694 |

Table 3. Component information of the RISAHS

The structural configuration of RISAHS adopted in the current design is a dispersed arrangement of the components. The system consists of six components which are regarded as one-component modules. The components are connected with each other by their functional as well as physical interactions. The function flows between the components in RISAHS are demonstrated as Figure 7-(a), while the physical links among them are depicted by a graph in Figure 7-(b). The value assigned to each edge of the graph stands for the number of links existing between two components.



(a) Function Flows among the Components



(b) Physical Links among the Components

Figure 7. Interactions among RISAHS Components

To assess the modularity of the system, Figure 8 illustrates the number of physical links, the level of similarity in service requirements, and the level of functional connectedness among the six modules. Again, the equal significance is considered for the effects of the ratio of intra-module physical links and the ratio of intra-module component life cycle correspondence.

On the basis of the information provided above, the CGV, FEU and LOM values are calculated for the engineering metrics, the components and the entire system. The results of the evaluation are presented in Table 4. Based on these technical characteristics, the result shows that the system has a *Medium*

| LINKS | C1 | C2 | C3 | C4 | C5 | C6 | SRS | C1 | C2 | C3 | C4 | C5 | C6 | FC | C1 | C2 | C3 | C4 | C5 | C6 |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| **C1** | 0 | 2 | 2 | 0 | 0 | 0 | **C1** | 1 | 0.3 | 0.3 | 0.8 | 0.8 | 0.9 | **C1** | 1 | 0.9 | 0.9 | 0.8 | 0.8 | 0.8 |
| **C2** | 2 | 0 | 10 | 2 | 2 | 2 | **C2** | 0.3 | 1 | 0.1 | 0.3 | 0.3 | 0.4 | **C2** | 0.9 | 1 | 0.5 | 0.4 | 0.5 | 0.5 |
| **C3** | 2 | 10 | 0 | 2 | 6 | 2 | **C3** | 0.3 | 0.1 | 1 | 0.3 | 0.3 | 0.2 | **C3** | 0.9 | 0.5 | 1 | 0.3 | 0.2 | 0.3 |
| **C4** | 0 | 2 | 2 | 0 | 0 | 0 | **C4** | 0.8 | 0.3 | 0.3 | 1 | 0.9 | 0.7 | **C4** | 0.8 | 0.4 | 0.3 | 1 | 0.8 | 0 |
| **C5** | 0 | 2 | 6 | 0 | 0 | 0 | **C5** | 0.8 | 0.3 | 0.3 | 0.9 | 1 | 0.7 | **C5** | 0.8 | 0.5 | 0.2 | 0.8 | 1 | 0 |
| **C6** | 0 | 2 | 2 | 0 | 0 | 0 | **C6** | 0.9 | 0.4 | 0.2 | 0.7 | 0.7 | 1 | **C6** | 0.8 | 0.5 | 0.3 | 0 | 0 | 1 |

Figure 8. Physical Links, Service Requirement Similarity and Functional Connectedness among RISAHS Components

| **Code** | **Weight** | **CGVi** | **CGVsys** | **PUI** | | | | |
|---|---|---|---|---|---|---|---|---|
| EM1 | 0.31 | 0.77 | **0.71** | **0.51** | | | | |
| EM2 | 0.08 | 0.86 | | | | | | |
| EM3 | 0.17 | 0.80 | | | | | | |
| EM4 | 0.06 | 0.91 | | | | | | |
| EM5 | 0.08 | 0.93 | | | | | | |
| EM6 | 0.10 | 0.54 | | | | | | |
| EM7 | 0.10 | 0.45 | | | | | | |
| EM8 | 0.10 | 0.45 | | | | | | |
| **Code** | **Weight** | **FRei** | **PRei** | **FEUi** | **FEUsys** | **CRi** | **CIi** | **LOM** |
| C1 | 0.10 | 0.91 | 0.84 | 0.91 | **0.83** | 1.00 | 0.12 | **0.25** |
| C2 | 0.10 | 0.12 | 0.98 | 0.34 | | 1.00 | 0 | |
| C3 | 0.05 | 0.99 | 0.69 | 0.84 | | 1.00 | 0 | |
| C4 | 0.25 | 0.78 | 0.90 | 0.87 | | 1.00 | 0.12 | |
| C5 | 0.35 | 0.78 | 0.92 | 0.87 | | 1.00 | 0 | |
| C6 | 0.15 | 0.91 | 0.95 | 0.95 | | 1.00 | 0.12 | |

Table 4. Upgradability evaluation results for the RISAHS

level of upgradability in the context of remanufacture after 5 years into its service life. It has a very good reusability due to the high reliability and technological maturity of its constituents. However, the low modularity of the system's structure coupled with a large number of inter-module physical links exhibits the downside of its configurations, suggesting that it might need a great amount of effort and/or time to disconnect those components during upgrade or reprocessing.

As the "weakest link", the structural features of the system need to be changed, if technically possible, in favour of upgradability improvement. On the other hand, in this evaluation approach only the number of links is considered to represent the complexity of the structural configuration of product or system. All types of physical links among components are treated equally regardless of their nature. Incorporating the severity ranking of each type of links with the number of links could be more informative in reflecting their impact on product upgradability. This issue will be considered in the refinement of the PURE approach.

## 5. Conclusion

This paper highlights the concept of product upgradability and its importance to the success of remanufacture. A new approach, the PURE (Product Upgradability and Reusability Evaluator), is proposed to model and assess the upgradability of a product in the context of remanufacture. By focusing on the essential technical characteristics, the upgrade potential of a product is measured at three domains of product representation, namely the engineering metrics domain, the component domain and the structural domain. Correspondingly, the indicators of compatibility to generational variety (CGV), fitness to extended utilisation (FEU), and life-cycle-oriented modularity (LOM) are proposed for the upgradability evaluation purpose. A simple example and a case study on a solar air heating system presented in this paper demonstrate that the results provided by the PURE are quite in line with common engineering knowledge about the technical features of product upgradability. Furthermore, the three indicators and their coefficients are able to provide companies good information about the readiness of the product to the given scenarios of upgrade at various levels (engineering metrics, component, and structure). Those values can be used for decision making in the redesign of the product, pointing out the aspects where improvements are needed. Nevertheless, a major drawback of the PURE model at this stage is that cost factors are not directly included in the modelling and evaluation of upgradability. Actually, one of the basic ideas for the development of this approach at this stage is to deliberately ignore the externality of cost and market issues and only focus on the essential roles of technical characteristics. The lack of economic perspective is acknowledged as one of the limitations of the current version of the approach. But, the development of this upgradability evaluation approach is just the first step of an ongoing research. In the next step, an approach for design optimisation of upgradability will be developed on the basis of PURE. Cost issues will be well considered by then and incorporated, as a major constituent, into the objective function. The other issues that are outside the scope of this paper include how to develop upgrade plans, how to identify planning horizon, and how to assess the possibility-to-change of components. These problems will be researched by our future work, together with the prediction of function/technology changes when a more comprehensive design framework is developed.

At this stage, the PURE is just a general framework for the representation and measure of product upgradability in the technical sense. Further refinement of the formulations of the three evaluation indicators or the inclusion of new indicators can be accommodated by the current structure of the PURE model to adapt to any particular products or upgrade scenarios.

## 6. Reference

Allen, K. R. and S. Carlson-Skalak (1998). Defining Product Architecture During Conceptual Design. Proceedings of DETC98: 1998 ASME Design Engineering Technical Conference, Atlanta, GA.

Beck, R. C. and S. E. Gros (1997). 'Remanufactured' Power Generation Equipement - An Economical Solution for Self-generation, Process or Peaking Applications. International Exhibition & Conference for the Power Generation Industries - Power-Gen, 1997.

Belusko, M., W. Saman, et al. (2004). "Roof Integrated Solar Heating System with Glazed Collector." Solar Energy 76(1-3): 61-69.

Blanchard, B. S., D. Verma, et al. (1995). Maintainability: A Key to Effective Serviceability and Maintenance Management. New York, Wiley & Sons.

De Souza, R. B., K. Ab, et al. (1996). "An Integrated Decision-Support Environment for DFX Audit." Journal of Electronics Manufacturing Vol. 6 , No. 3: 163-171.

Droda, T. J. (1984). "Machine Tool Remanufacturing." Manufacturing Engineering 92(2): 88-98.

Hata, T., S. Kato, et al. (2001). Design of Product Modularity for Life Cycle Management. Proceedings of 2nd International Symposium On Environmentally Conscious Design and Inverse Manufacturing, 2001, Eco'01.

Huang, G. Q. (1996). Design for X: Concurrent Engineering Imperatives. London, Chapman & Hall.

Ijomah, W., J. P. Bennett, et al. (1999). Remanufacturing Evidence of Environmental Conscious Business Practice in UK. EcoDesign 99': First International Symposium on Environmentally Conscious Design and Inverse Manufacturing, 1999., Tokyo.

Ishii, K., C. F. Eubanks, et al. (1994). "Design for Product Retirement and Material Life-Cycle." Materials & Design **15(4)**: 225-233.

Ishigami, Y., H. Yagi, et al. (2003). Development of A Design Methodology for Upgradability Involving Changes of Functions. Proceedings of the 3rd International Symposium on Environmentally Conscious Design and Inverse Manufacturing, EcoDesign '03.

Li, F.-Y., G. Liu, et al. (2000). "A Study on Fuzzy AHP Method in Green Modularity Design." China Mechanical Engineering (In Chinese) **11(9)**.

Li, J.-z., P. Shrivastava, et al. (2004). A Distributed Design Methodology for Extensible Product Life Cycle Strategy. Proceedings of IEEE International Symposium on Electrionics and the Environment 2004.

Newcomb, N. J., B. Bras, et al. (1998). "Implications of Modularity on Product Design for the Life Cycle." Journal of Mechanical Design vol. 120: pp 483-490.

Overfield, J. A. (1979). Maintenance and Remanufacturing of Injection Molding Machines. Chicago, National Bureau of Standards, Inject Molding Division and Chicago Section: X.1-X.7.

Pridmore, J., G. Bunchanan, et al. (1997). "Model-Year Architectures for Rapid Prototyping." Journal of VLSI Signal Processing 15: 83-96.

RMIT (2001). EcoRedesign Guidlines,

http://www.cfd.rmit.edu.au/outcomes/erdnews/ERD1/ERDguide.html (29/06/2001 & 04/07/2001).

Rose, C. M. (2000). Design for Environment: A Method for Formulating Product End-of-Life Strategies. Dept. of Mechanical Engineering. Stanford, Stanford University: pp 185.

Shimomura, Y., Y. Umeda, et al. (1999). A Proposal of Upgradable Design. Proceedings of First International Symposium On Environmentally Conscious Design and Inverse Manufacturing, EcoDesign '99.

Umemori, Y., S. Kondoh, et al. (2001). Design for Upgradable Products Considering Future Uncertainty. Proceedings of EcoDesign 2001: Second International Symposium onEnvironmentally Conscious Design and Inverse Manufacturing, 2001.

Wang, J., G. Duan, et al. (1999). "Current Situation and Future Developing Trends of Green Manufacturing Technology Based on Products'Life Cycle." Computer Integrated Manufacturing System, CIMS (In Chinese **5(4)**: 1-8.

Well, R. (2004). Make it New. Aviation Week and Space Technology. 161: 56-57.

Wilhelm, W. E., P. Damodaran, et al. (2003). "Prescribing the Content and Timing of Product Upgrades." IIE Transactions 35(7): 647-663.

Xing, K., L. Luong, et al. (2002). The Development of A Quantitative Method for Product End-of-Life Strategy (EOLS) Planning. Proceedings of 4th International Symposium on Tools and Methods of Competitive Engineering (TMCE) 2002.

Xing, K. (2003). Development of An Integrated Framework for Design for Recyclability. School of Adv. Manufacturing & Mechanical Engineering. Adelaide, SA, University of South Australia: 239.

Xing, K., B. Motevallian, et al. (2003). A Fuzzy-graph based Product Structure Modularisation Approach for Ease-of-recycling Configuration. Proceedings of 9th International Conference on Manufacturing Excellence, ICME 2003.

Zadeh, L. A. (1965). "Fuzzy Sets." Information and Control 8: 338-353.