## UNIVERSIDAD NACIONAL AUTÓNOMA DE MÉXICO

FACULTAD DE INGENIERÍA

***ANÁLISIS COMPARATIVO DE UN COMPONENTE HECHO DE DIFERENTES MATERIALES PARA DETERMINAR EL ECOLÓGICAMENTE MEJOR***

# TESIS

QUE PARA OBTENER EL TITULO DE:

**INGENIERO MECÁNICO**

P R E S E N T A :

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## DEDICATORIAS

A Dios.

A mis padres Federico y María Raquel, porque gracias a su esfuerzo pude concluir mi carrera.

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# INTRODUCCIÓN

## Ideas Generales

En La Tierra, un planeta con recursos limitados y graves impactos ambientales, resulta evidente que un planteamiento sustentable del estilo de vida será cada vez más importante. Productos como: grapas, televisores o vehículos, son ejemplos de cosas que, pueden estar hechos de un solo material o de una gama de diferentes materiales. Algunas estimaciones nos dicen que tenemos que lidiar probablemente con más de 100,000 materiales comerciales existentes en el mercado con respecto a la gran cantidad de variantes [1]. La extracción, refinación, transporte, la fase del uso del producto, el reciclado o la deposición, son ejemplos de ámbitos complejos que pueden producir diferente tipo de impactos sobre el medio ambiente.

Durante el último siglo, las cuestiones ambientales podrían considerarse a menudo como problemas locales debido al impacto de un determinado producto. Sin embargo, cada vez se hace más evidente que éstos son mucho más complejos y relacionados con todas las fases del ciclo de vida del producto desde la extracción del material hasta la deposición de residuos o de los productos utilizados anteriormente.

Existen hoy en día por lo menos cuatro problemas básicos, que no han sido resueltos satisfactoriamente, éstos son: El exceso en el consumo, la utilización desmedida de los recursos naturales, la contaminación y la sobre-población [1].

- Exceso en el consumo: El uso de los materiales en las fases de producción de energía, el empaquetado y manufactura de los productos, ha aumentado por lo menos 20 veces per cápita en muchos países altamente industrializados desde el final del siglo 19 hasta el día de hoy [2,3]. Más componentes y más materiales mixtos son utilizados en diferentes productos, lo que demanda transporte, en combinación generalmente con mayor consumo de energía en todo el mundo, son sólo ejemplos de un exceso en el consumo. La naturaleza no puede mantener la actual tasa de crecimiento de hasta aproximadamente un 5% en algunos países, sin graves consecuencias a largo plazo [4].

- La utilización desmedida de los recursos naturales: La humanidad no ha sido capaz de cooperar con la naturaleza en relación con la sustentabilidad. Hoy en día se desperdicia un gran porcentaje del material y la energía necesarios para la producción de bienes o servicios en aspectos que no tienen que ver con el producto en sí. Una gran cantidad de energía y materiales, por ejemplo, se perdieron durante la producción de materias primas, transporte, empaquetado etc. Esto incluye el material de desecho y las emisiones, especialmente para los productos no reciclables.

- Contaminación: Incluso si todas las empresas lograran cero emisiones ahora mismo, la tierra seguiría siendo gravemente afectada por las emisiones generadas hasta la fecha [5]. Y esto aunado a que en lugar de disminuir las emisiones, cada día aumentan más, sugiere que el problema será cada vez más grave.

- El exceso de población: Si el mundo tuviera más de diez mil millones de habitantes para el año 2025, esa situación se traduciría en una disminución de la sustentabilidad, provocando más y más impacto ambiental. Aun cuando muchos productos como por ejemplo los automóviles, se han hecho más amigables para el medio ambiente durante las últimas décadas, como el caso de los automóviles híbridos, estos obviamente no pueden reducir la cantidad total de los materiales y la energía utilizada debido al aumento de la población.

Sin embargo, no hay posibilidades de reducir todos los impactos ambientales a cero. El aumento de la entropía en la Tierra es un hecho, que ha sido constatado por la 2a ley de la Termodinámica [6], esto implica que no se puede regresar a un estado inicial en el que la contaminación sea cero. Es evidente que la Tierra está poblada por sus habitantes (animales, plantas, bacterias, etc. Que transpiran y generan calor) y esto provoca una situación que es “no sustentable por sí misma”.

En esta Tesis se hará un ejercicio, aplicando los métodos que idearon los investigadores Lennart Y Ljunberg. [1]; Sami Kara, et al [7]; U. Woy, et al [8]; Hwai-En, et al [9]; S. Jawahir, et al [10]; para tratar de lograr que el desarrollo de la sociedad en general sea más sustentable.

Estos autores proponen métodos, herramientas e incluso planes de estudio para lograr este fin. Con ello se hizo una comparación a fin de mostrar la importancia de este tipo de estudios.

Luego se realizará una comparación para establecer en base a estos métodos, cuál o cuáles son los más apreciables a nuestro interés.

## Hipótesis

*La hipótesis de este trabajo es:*

*"Si se obtiene el indicador ecológico del ciclo de vida de un componente, entonces se podrá determinar el impacto ambiental de dicho componente y si se compara ese indicador con el de otro componente que realiza la misma función pero que es diferente en algunos aspectos (e.g. materiales y/o proceso de manufactura) entonces se podrá determinar cuál es el mejor en términos de ecología."*

*Y vamos a probarla haciendo el análisis comparativo de una carcasa o chasis hecho de dos materiales distintos, aluminio anodizado y ABS.*

# Objetivo

El objetivo de esta Tesis es la estimación del indicador ecológico de un componente hecho de un material dado, durante su ciclo de vida completo, y compararlo con el indicador de ese mismo componente pero fabricado de un material distinto, para así comprobar la hipótesis para este caso de estudio específico. Se emplea como ejemplo la carcasa de un lente motorizado que se utiliza en la toma de imágenes en laboratorios farmacéuticos y de biotecnología.

Metodología:

La manera en que se llevó a cabo el ejercicio fue cumpliendo con los siguientes pasos:

1) Revisar y comparar 5 métodos de evaluación de carga ecológica, seleccionar uno de entre los mostrados.

2) Complementar el método seleccionado con la herramienta del Eco-indicador 99.

3) Concluir y recomendar con base en el puntaje de los resultados obtenidos.

# CAPÍTULO 1: DEFINICIONES

## Definiciones Generales:

### Sustentabilidad

La sustentabilidad fue definida por la Comisión Mundial de Medio Ambiente y Desarrollo de Naciones Unidas como: “satisfacer las necesidades de las generaciones presentes sin comprometer las posibilidades de las futuras generaciones de conocer sus propias necesidades” [11].

Por esto mismo que no sólo nos debemos preocupar por la naturaleza sino que las personas son importantes también. Un ambiente sin personas en realidad no es el ambiente.

Es por esto que el desarrollo sustentable tiene tres componentes esenciales que deben tenerse en cuenta y son igualmente importantes para lograr un futuro mejor: el ambiente, la sociedad y la economía [6] como se muestra en la figura 1.

Es decir que la idea no es tener más y más cosas sino tener una mejor calidad de vida. Y no podemos tener una mejor calidad de vida si no tenemos educación, no hay justicia, si la inseguridad sigue creciendo. Como tampoco podemos si el planeta está contaminado y los recursos naturales no alcanzan.

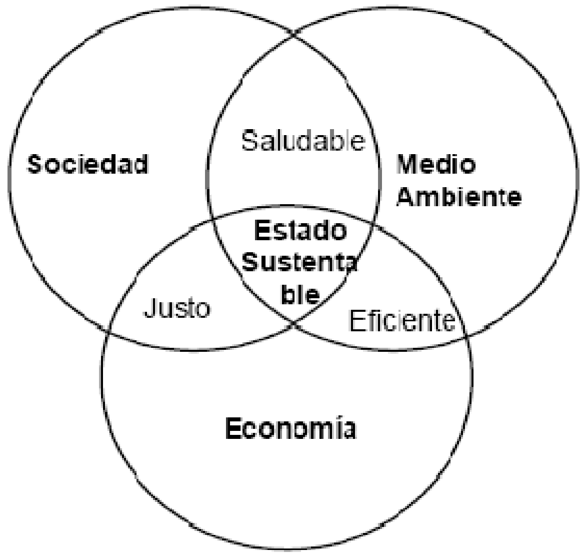



**Fig. 1 Estado Sustentable: Equilibrio entre Sociedad, Medio Ambiente y Economía**

Desarrollo sustentable

Los siguientes conceptos son ejemplos importantes relacionados con el desarrollo sustentable, según Ljunberg [1].

- Medio ambiente: El ecosistema mundial debe ser tratado con el fin de proteger no sólo las plantas y los animales, sino también recursos minerales, y demás organismos y objetos que lo constituyen. El medio ambiente debe considerarse como parte del proceso de desarrollo y no deben tomarse de forma gratuita para su uso.

- Equidad: La cuestión de la pobreza y la igual distribución en el uso de fuentes naturales debe resolverse a fin de mantener sociedades estables y equitativas.

- Porvenir: El impacto del desarrollo debe ser visto en una perspectiva a largo plazo con el fin de minimizar el impacto para las generaciones futuras y así permitir que estas sean capaces de descubrir y resolver sus propios problemas, sin tener que lidiar con los problemas heredados.

## Producto sustentable

No hay una manera simple de desarrollar "productos sustentables". La complejidad de la situación ya ha sido presentada anteriormente y de acuerdo a las leyes termodinámicas, productos totalmente sustentables no son posibles de desarrollar en general. Sin embargo, hay muchos diferentes enfoques y definiciones de cómo desarrollar productos sustentables, que serán estudiadas y analizadas en este documento. El principal problema que sigue sin resolverse es el hecho de que el mundo no es sustentable por sí mismo. La vida en la tierra no puede seguir para siempre en una forma que la naturaleza pueda volver a algún tipo de condición inicial sin una drástica influencia de los sistemas fuera de la Tierra causando una reducción de la entropía en nuestro sistema terrestre. La mayoría de las definiciones de productos sustentables entre los investigadores en este ámbito han puesto de manifiesto la falta de comprensión del hecho de que nuestro planeta no es un sistema sustentable por sí mismo. Sin embargo, la definición siguiente se aplicará en el presente documento:

Un producto sustentable, es un producto que, provocará tan poco impacto sobre el medio ambiente como le sea posible durante su ciclo de vida [1].

El ciclo de vida en esta simple definición incluye la extracción de materias primas, producción, uso y reciclaje final (o deposición). El material contenido en el producto, así como el material (o elemento) utilizados para la producción de energía también se incluyen aquí. Esta definición, de hecho, no está totalmente acotada de acuerdo a la cantidad de impacto sobre el medio ambiente o la naturaleza. De ahí que el impacto no puede ser cero, debe ser "razonablemente reducido al mínimo". Esto abre el hecho de que se produzca productos similares, que son "sustentables" en mayor o menor grado cuando son comparados uno al lado del otro.

Como puede entenderse desde arriba, hay muchos diferentes aspectos y detalles relacionados con esta definición. En este documento se elucidará el desarrollo de productos sustentables mediante la presentación de algunos aspectos importantes para luego examinar los medios para medir la sustentabilidad.

### Indicador ecológico

Es la cantidad obtenida a partir de un modelo, la cual representa la relación entre el impacto ambiental y el daño que representa para los humanos o el ambiente [12,13].

### Ciclo de vida de un producto

Es el proceso que sigue un producto desde la extracción de los materiales primarios, hasta que es reciclado o desechado. El Análisis de Ciclo de Vida (LCA life cycle assessment) es una herramienta útil para comprender el impacto del medio ambiente. Es cuando el producto se evalúa paso a paso a lo largo de toda su vida “desde la cuna a la tumba”. Donde costos, impacto, esperanza de vida, etc. pueden ser evaluados de una manera bastante fácil [1].

# CAPÍTULO 2: MÉTODOS Y ACCIONES PROPUESTAS EN LA LITERATURA PARA INCREMENTAR LA SUSTENBILIDAD

En el presente capítulo se resumen 5 de las metodologías reportadas hoy en día en la literatura y que a mi juicio constituyen propuestas que pueden ayudar al diseñador a la creación de productos más sustentables, de las cuales presento su concepto en forma resumida y un diagrama de cada una:

## *1. MATERIALS SELECTION AND DESIGN FOR DEVELOPMENT OF SUSTAINABLE PRODUCTS LENNART Y. LJUNGBERG **

*Selección de materiales y diseño para el desarrollo de productos sustentables. Publicado por Lennart Y. Ljunberg [1].*

El autor hace una revisión de métodos actuales y de modelos, sobre la forma de desarrollar productos sustentables. Aquí muestran diferentes métodos para lograr productos con tan bajo impacto ambiental como sea posible, así como los principios para el desarrollo de productos especiales, considerando: la selección de materiales, diseño, el uso y el reciclado.

Definición de un producto sustentable, la triple línea de base, la desmaterialización, el reciclado, consideraciones de diseño, norma ISO 14001 y el EMAS, esquema de gestión y auditoria medioambiental (*Eco Management and Audit Scheme*). Estos son algunos de los ejemplos, los cuales son revisados en este artículo.

También se examinan: la evaluación del ciclo de vida, impacto ambiental, eco-eficiencia, espacio ambiental, contactos en el mercado, los aspectos culturales, la moda y las tendencias.

Con especial atención en los materiales, el diseño y la ecología, que representan directrices para el desarrollo de productos sustentables. Algunas de estas se abordarán más adelante.

También se presenta una descripción de selección de materiales y modelos para el diseño basado en una sociedad sustentable

La mayor ventaja que se encuentra en este documento es que a diferencia de la mayoría, en este se explica a fondo la importancia del desarrollo de productos sustentables. Aunque no ofrece un caso de estudio o un ejemplo en concreto, sirve de guía al lector, para aplicarse a un producto real. En particular para esta Tesis, este artículo ofrece la posibilidad de ser aplicado tanto a un nuevo diseño como a un objeto que ya esté presente en el mercado. Por lo que no sólo puede aplicarse en la etapa de diseño, sino que también se puede evaluar la sustentabilidad de un producto existente.

Observo una gran desventaja en este artículo. No presenta un ejemplo didáctico en el cual se pudiera ver mejor lo que propone. Además de que al considerar tantos elementos para el desarrollo de productos sustentables, es fácil divagar entre uno y otro. También observo que no cuenta con una herramienta cuantitativa para llevar a cabo dicho estudio.

Fig. 2 diagrama del artículo: Selección de materiales y diseño para el desarrollo de productos sustentables. Publicado por Lennrt Y. Ljunberg.

## *2. AN INTEGRATED FRAMEWORK FOR IMPLEMENTING SUSTAINABLE PRODUCT DEVELOPMENT SAMI KARA, INA HONKE, HARTMUT KAEBERNICK, THE UNIVERSITY OF NEW SOUTH WALES, TECHNICAL UNIVERSITY OF HAMBURG,*

*Marco integrado para implementarse durante el desarrollo de un producto sustentable. Desarrollado por: Sami Kara, Ina Honke y Harmut Kaebernick [7].*

Este trabajo presenta un marco integrado para la aplicación en el Desarrollo de productos sustentables (SPD). El enfoque se centra en la integración de la sustentabilidad del medio ambiente en las empresas manufactureras con el control sobre los procesos clave de desarrollo de productos, sobre todo las primeras fases, ya que estos son los actores clave en el diseño y fabricación de productos. A partir del análisis de los mejores desarrollos disponibles desarrollados por los investigadores y la industria y los instrumentos adecuados. Las actividades a desarrollar dentro de la empresa se vinculan con los tres niveles de ejecución como precursoras para la aplicación del SPD. El enfoque propuesto combina la precisión estratégica y enfoques operacionales en un marco único.

La principal ventaja de este marco integrado es que se centra en las primeras fases del desarrollo del producto, por lo que es más fácil reducir los impactos.

Sin embargo para efectos de esta Tesis la mayor desventaja es que este marco se orienta a actividades de empresas manufactureras. Por debe contarse con la facilidad de estar adentro de una de estas empresas. De otro modo sería difícil aplicarlo para llegar a un resultado positivo. Otro problema de este método, es el hecho de que no presenta una aplicación concreta en algún producto o servicio, ni siquiera menciona alguna empresa en la cual se haya hecho algo de acuerdo a lo mencionado en el documento.

Fig. 3 Diagrama del artículo: Marco integrado para implementarse durante el desarrollo de un producto sustentable. Desarrollado por: Sami Kara, Ina Honke y Harmut Kaebernick

### *3. NEW PRODUCT DEVELOPMENT: IMPLEMENTING PROCEDURES FOR SUSTAINABLE PRODUCT DEVELOPMENT IN SMEs UTILISING AVAILABLE TECHNOLOGIES U. Woy*, Q. Wang*

*Implementación de procedimientos para el desarrollo de productos sustentables en PYMES utilizando tecnologías disponibles. Hecho por U. Woy, Q Wang [8].*

El artículo menciona que pequeñas y medianas empresas (PYMES), particularmente en el Reino Unido, participan cada vez más en el desarrollo de nuevos productos (NPD) por una ventaja competitiva. Con recursos limitados y la experiencia en nuevos productos y procesos de desarrollo, la introducción y aplicación de los riesgos asociados son significativamente más elevados para todos los interesados. En este trabajo veremos que la planificación de recursos empresariales (ERP) es la herramienta utilizada para proporcionar una visión de la relación entre la aplicación de la tecnología, la participación personal y el desarrollo de productos sustentables en un subcontrato de fabricación para las PYMES. El objetivo es proporcionar una estrategia de desarrollo de productos apoyados por los procedimientos a través de la utilización de las tecnologías avanzadas disponibles.

La principal ventaja para el procedimiento que se encuentra en este documento para el desarrollo de productos sustentables, es que se ocupa la pequeña y mediana empresa como medio para llegar a tal fin. Es decir que no sólo las grandes empresas pueden lograr productos más amigables con el ambiente, sino también las denominadas MIPYMES.

Los siguientes procedimientos presentan una desventaja. Esta reside en que se presenta como tema central de la discusión la parte administrativa de dichas empresas. En concreto la que fue el caso de estudio. Por lo tanto sería algo difícil aplicar los procedimientos de este documento para el caso de estudio de esta Tesis. Otra cuestión por la que este artículo no es aplicable a esta Tesis es que la sustentabilidad del producto la centran más en lo económico y social que en lo ecológico.

El caso de estudio que se presenta en este documento es el de la empresa Dyer Engineering Ltd. En el noreste de Inglaterra. El cual ofrece como resultado según un mapeo que se hizo en dicha empresa que más recursos son requeridos durante las últimas etapas del proceso opuesto con el tiempo durante el cual se consume la naturaleza en las etapas iniciales.

Fig. 4 Diagrama del artículo: Implementación de procedimientos para el desarrollo de productos sustentables en PYMES utilizando tecnologías disponibles. Hecho por U. Woy, Q Wang

## *4. MODULAR DESIGN TO SUPPORT GREEN LIFE-CYCLE ENGINEERING HWAI-EN TSENG A,*, CHIEN-CHEN CHANG B, JIA-DIANN LI A*

*Diseño modular como soporte de Ingeniería de ciclo de producto verde. Desarrollado por Hwai-En Tseng a,*, Chien-Chen Chang b, Jia-Diann Li A [9].*

El autor explica en este texto como la fuerte competencia en el mercado ha impulsado a las empresas a producir una mayor variedad de productos para satisfacer las necesidades de los consumidores. Sin embargo, las frecuentes variaciones de las especificaciones del producto hacen que el ensamble y des-ensamblaje de los componentes y módulos tiendan a ser más y más complicados. Como resultado de ello, la cuestión de diseño modular de productos es un problema digno de preocupación. En este estudio se añadieron a un modelo gráfico de enlaces, algunos atributos de ingeniería para la evaluación de la conexión entre las distintas partes. Los atributos de ingeniería añadidos, incluidos los de tipo de contacto, el tipo de combinación, tipo de instrumento y de dirección de acceso, servirán para ofrecer a los futuros diseñadores, criterios para evaluar la intensidad de enlace durante la etapa de diseño. Además se hace referencia a un algoritmo genético de agrupamiento (GGA) que es empleado posteriormente para agrupar los componentes y mecanismos de cruce a fin de modificar el diseño modular de acuerdo a las necesidades que en ese momento surjan. Por otra parte, se realiza una evaluación del diseño verde modular razonable mediante el análisis de costos del material verde. Según los resultados, las propuestas de diseño ajustadas que se sugirieron y el uso de materiales que causaron menos contaminación fueron los recomendados para sustituir los componentes con los valores de contaminación superiores a los hallados en el módulo. Por último, los autores recomiendan el uso de Borland C++ 6,0 para evaluar el sistema y el método de agrupación. Para ilustrar la metodología propuesta en este estudio, una lámpara de mesa se ofrece como un ejemplo.

La ventaja principal de este documento, es el empleo de tablas de datos que ofrecen un método de evaluación cuantitativo, fácil de aplicar en casi cualquier caso de estudio y con un ejemplo bien detallado que en este caso fue una lámpara.

Sin embargo un poco más adelante se habla de uso de algoritmos genéticos usados como herramienta de mejora para futuros diseños, y el problema radica en que al no ofrecerse ningún detalle del software utilizado, resulta muy complicado aplicar esta etapa del análisis a nuestro caso de estudio.

Fig. 5 diagrama del artículo: Diseño modular como soporte de Ingeniería de ciclo de producto verde. Desarrollado por Hwai-En Tseng a,*, Chien-Chen Chang b, Jia-Diann Li A

### *5. DESIGN FOR SUSTAINABILITY (DFS): NEW CHALLENGES IN DEVELOPING AN IMPLEMENTING A CURRICULUM FOR NEXT GENERATION DESIGN AND MANUFACTURING ENGINEERS: I. S. JAWAHIR, K. E. ROUCH, O. W. DILLON, JR., L. HOLLOWAY, AND A. HALL*

*Nuevos retos en el desarrollo e implementación de un programa de estudio para la siguiente generación de ingenieros de manufactura y/o diseño. Desarrollado por: I. S. Jawahir, K. E. Rouch, O. W. Dillon, Jr., L. Holloway, and A. Hall [10].*

En este documento se menciona principalmente la existencia de tendencias innovadoras en el diseño del producto y la fabricación. Esto exige un cambio de paradigma en las metodologías tradicionales  porque son cada vez más ineficaces al momento de aplicarlas para la construcción de un futuro más sustentable. El conocido concepto de desarrollo sustentable, que se basa en un crecimiento sostenido del medio ambiente, beneficios económicos y sociales, es calificado, destacando la importancia del diseño de producto y la fabricación. Esto es que los retos tecnológicos deben resolver la necesidad de aplicar un diseño innovador y un proceso de fabricación llamado a cubrir la necesidad de elaboración y aplicación de nuevos programas educativos y de formación para la próxima generación de ingenieros de diseño y manufactura. El objetivo que plantea este documento, es hacer frente a estos desafíos con una nueva propuesta de plan de estudios. Perpetuar el flujo de materiales y múltiples ciclos de vida, usos y materiales auto-reparables, productos y procesos innovadores de diseño y desarrollo se encuentran en el núcleo de los programas de educación de diseño para lograr la sustentabilidad que se propone en este artículo.

Este documento plantea el método tal vez más ambicioso a largo plazo, ya que, plantea la formación de profesionistas desde las aulas de universidades e institutos que tengan un enfoque de ingeniería sustentable, que por consecuencia, este concepto esté siempre presente mientras el ingeniero diseña o realiza cualquier otra actividad dentro de su campo de trabajo.

La gran desventaja de este método o programa de estudio, es que no se puede saber por el momento que tan grande y efectivo será su impacto, ya que, como el mismo documento menciona, esto se vería reflejado hasta que surja la nueva generación de ingenieros formados bajo este plan de estudio.

Fig. 6 diagrama del artículo: Nuevos retos en el desarrollo e implementación de un programa de estudio para la siguiente generación de ingenieros de manufactura y/o diseño. Desarrollado por: I. S. Jawahir, K. E. Rouch, O. W. Dillon, Jr., L. Holloway, and A. Hall

Comparación de los métodos y acciones propuestas

| **Criterios** / **Método** | *Se puede aplicar durante las fases de diseño o antes* | *Tiene algún modo sencillo de medirse la mejora* | *Involucra la formación de recursos humanos que lo podrán aplicar sistemáticamente* | *Se puede aplicar para este trabajo de Tesis* | *Es comprensible el método o propuesta de tal modo que un Ingeniero en formación lo pueda aplicar* |
|---|---|---|---|---|---|
| **1.Selección de Materiales** | **SI** | **SI** | **NO** | **SI** | **SI** |
| **2.Marco Integrado** | **SI** | **NO** | **NO** | **NO** | **NO DEL TODO** |
| **3. PYMES** | **NO** | **NO** | **SI** | **NO** | **NO DEL TODO** |
| **4. Diseño Modular** | **SI** | **SI** | **NO** | **SI** | **NO DEL TODO** |
| **5. Plan de estudios** | **NO** | **NO** | **SI** | **NO** | **NO DEL TODO** |

*Tabla 1 Comparativo de las 5 acciones mencionadas anteriormente. A cada una se le asigna una calificación cualitativa de acuerdo con el criterio que se considera importante para llevar a cabo el objetivo planteado para esta Tesis. "SI" implica una ventaja de dicho método o acción, "NO" implica una desventaja y "NO DEL TODO" implica cierta ambigüedad o dificultad en los conceptos o en cómo aplicarlos.*

De la tabla se puede ver que el método que mejor se ajusta para el trabajo de análisis hecho en esta tesis es el número 1. Selección de materiales, ya que, de acuerdo a los criterios presentados en la tabla, es el que mejor se adecua a nuestros propósitos.

Criterio número 1 *¿Se puede aplicar durante las fases de diseño o antes?* Los métodos que tienen mejores características de a cuerdo a este criterio son los de: selección de materiales y diseño modular, el método que se refiere al marco integrado tiene ciertas características aplicables al diseño del producto, pero se orienta más al control de procesos.

Criterio número 2 *¿Tiene algún modo sencillo de medirse la mejora?* Los métodos de selección de materiales y de diseño modular son los que mejor cumplen con ese criterio, aunque el de selección de materiales se complementará con otra herramienta, eso se puede ver en el capítulo 3 de esta Tesis.

Criterio número 3 *¿Involucra la formación de recursos humanos que lo podrán aplicar sistemáticamente?* Sólo los métodos del plan de estudios y de PYMES tienen características suficientes para considerar que si cumplen con el criterio 3, y cabe notar que es el único criterio que el método de selección de materiales no cumple.

Criterio número 4 *¿Se puede aplicar para este trabajo de Tesis?* Los métodos que van de acuerdo con este criterio son: el de selección de materiales y el de diseño modular.

Criterio número 5 *¿Es comprensible el método o propuesta de tal modo que un Ingeniero en formación lo pueda aplicar?* El único método que tiene todas las características necesarias para cumplir con el criterio es el de selección de materiales, el método de diseño modular tiene ciertos puntos que si cumplen con el criterio, sin embargo tiene la gran desventaja de que para el rediseño de la lámpara (que es su caso de estudio) ocupaban algoritmos genéticos, algo que esta fuera de los alcances de esta Tesis.

Los cinco criterios mencionados son los que se consideran como más importantes para llegar a un producto sustentable.

Ya que se eligió el método de selección de materiales como el que se aplicará al caso de estudio, se mencionarán los puntos más importantes que plantea dicho método y que en el documento se mencionan como las directrices para el desarrollo sustentable.

Método que sigue el criterio de selección de materiales

- Reducir los materiales y la utilización de la energía de un producto, incluidos los servicios durante su vida.
- Reducir las emisiones, la dispersión y la creación de sustancias tóxicas durante su vida.
- Aumentar la cantidad de materiales reciclables.
- Maximizar el uso sustentable de los recursos renovables.
- Extender la vida útil de un producto.
- Evaluar y minimizar el impacto medioambiental del producto a lo largo de toda la vida.
- Tener una “economía funcional” es una forma de sustituir los productos con servicios.
- Utilizar la “lógica inversa” lo que significa que todos los esfuerzos se enfocan con el fin de reutilizar los productos y materiales.
- Aumentar la eficacia de un producto en la fase de uso.

Sin embargo no todas serán abordadas en este trabajo de Tesis y hay algunas más que no se mencionan.

El método de “Selección de materiales y diseño para el desarrollo de productos sustentables, desarrollado por Lennart Y. Ljunberg [1]” para realizar la comparación es cualitativo, por lo que se decidió emplear una herramienta adicional, el Eco-indicador 99 [13], el cual dentro de su manual de uso proporciona unas tablas con información cuantitativa para medir la carga ambiental de un producto durante todo su ciclo de vida.

Historia y descripción del Eco-indicador 99 [13].

PRE (product ecology) Consultores, es una empresa holndesa que desde 1990 está dedicada al estudio del desarrollo del Análisis de Ciclo de Vida, con métodos, herramientas de software y consultoría. Esta empresa tiene la misión de hacer un cambio positivo en el mundo, proporcionando las herramientas, el conocimiento y la red para ayudar a la toma de decisiones para la ordenación sustentable de las políticas, productos y servicios [12].

En 1995 los diseñadores se dieron cuenta que necesitaban una referencia para medir el impacto ambiental de un material o proceso. El Eco-indicador 95 (EI95) se desarrolló para proporcionar esa herramienta, y fue uno de los primeros en expresar la carga ambiental total de un material o proceso con una puntuación única. Sin embargo, aunque el EI95 fue muy utilizado por los diseñadores, fue muy duramente criticado por expertos ya que no tomaba en cuenta varios aspectos a cerca del medio ambiente. Así que en 1999 se creó el método EI99 que incluía muchos más aspectos y por lo mismo es más completo que el EI95.

El EI99 califica todo el ciclo de vida de un producto de manera cuantitativa como se ve en el manual del EI99 [13]. En las tablas que contiene dicho manual se observan claramente las etapas del ciclo de vida de los productos, y además a cada uno le corresponde un valor del indicador (expresado en mp que equivale a la unidad de carga ecológica expresada en milipuntos) dependiendo de algunas consideraciones que específica el manual, tales como: el peso del objeto, el material obviamente, el proceso de producción tanto de las materias primas como el proceso de conformado, etc.

También en el Eco-indicador 99 se presentan las directrices para la selección de materiales durante el diseño de productos sustentables.

Los materiales y su descripción

Un producto técnico esta generalmente hecho de uno o varios materiales. Sin embargo, hay ejemplos de productos inmateriales, como los programas de computación. La sustentabilidad de un determinado producto material se basa principalmente en función del material o materiales utilizados para el producto en sí o durante su vida de acuerdo con un ACV (Análisis de Ciclo de Vida, o LCA por sus siglas en inglés “Life Cycle Assessment”) por ejemplo. Durante el ciclo de vida de un producto material, las distintas etapas que se pasan son: la extracción de material, fabricación, envasado, transporte, el uso del producto y la eliminación. Todas estas etapas darán un cierto impacto ambiental, que es causado principalmente por los materiales que intervienen en las distintas etapas [2,4]. Por lo tanto, la selección de materiales para un determinado producto es de vital importancia, mientras que el material determina el uso de nuestros recursos naturales, así como la cantidad de energía utilizada para la producción y el uso del producto. La fabricación de productos típicamente involucra sustancias químicas como los fluidos de corte durante el mecanizado, auxiliares de limpieza, pintura, etc. Tiempo de vida, mantenimiento, servicio técnico y reparación de un producto, son otros ejemplos de áreas que son generalmente dependientes del material utilizado para el producto en sí.

El uso de materiales renovables, como la madera frente a los materiales no renovables, como los plásticos (derivados de petróleo), es también importante tenerlo en cuenta en el desarrollo de productos. Materiales renovables son los materiales que en un breve espacio de tiempo se pueden formar de nuevo en la naturaleza y causar nulo o muy poco impacto sobre el medio ambiente. Si, por ejemplo, un árbol se corta, se utiliza en un producto y se quema y un nuevo árbol se planta, el nuevo árbol puede capturar las emisiones de dióxido de carbono que se forman cuando el viejo árbol es quemado. Si las cenizas, que contienen minerales y fertilizantes, se traen de vuelta a la tierra, el nuevo árbol las utilizará mientras crece. Este es un ejemplo del ciclo de vida de un material renovable. Sin embargo, si un bosque se ha reducido y no se han plantado nuevos árboles, el equilibrio ambiental cambia. Esto puede conducir a la destrucción de la tierra, un cambio en el clima debido a un cambio en el balance hídrico y en el peor de los casos la formación de un desierto. Cuando un árbol se corta se puede estimar un precio para garantizar la sustentabilidad, en este caso significa que un nuevo árbol se planta y los bosques son conservados y mantenidos en el futuro. Un polímero derivado de petróleo es un ejemplo de un material no renovable, debido a que el petróleo crudo no es fácil de ser llevado a su estado inicial una vez más, esta acción conduce a un impacto ambiental cuando el petróleo crudo se utiliza. Por lo tanto los materiales orgánicos son los que se consideran como materiales renovables.

La selección de materiales es tradicionalmente determinada por las exigencias técnicas como el precio, resistencia de materiales, estabilidad térmica, densidad, dureza, etc. Sin embargo, las exigencias técnicas o físicas no son suficientes para el éxito del desarrollo del producto. Se deben de tomar en cuenta otros factores como la moda, aspectos culturales, etc. Por ejemplo, el caso de la ropa hecha de fibras sintéticas que a menudo son más fáciles de limpiar y mantener libre de arrugas, que las de los materiales naturales, sin embargo los últimos generalmente son más populares debido a su sensación y otros factores. Los suelos de madera son más populares para ciertas personas, aunque los de hormigón sean más duraderos y resistentes al desgaste. En cualquier caso, la selección de materiales para productos sustentables se basa principalmente en el impacto final sobre la naturaleza, así como en las demandas del mercado y en los factores económicos.

Las estimaciones nos dicen que hay más de 100,000 diferentes tipos de materiales comerciales en el mercado [1] si se incluyen todas las variantes en los materiales, como: composición, mezcla, tratamiento térmico, etc. El hecho es que deben ser considerados no sólo métodos objetivos para la selección de materiales, sino también subjetivos que no hacen más fácil la selección. Es la siguiente división de los materiales en los grupos una forma de simplificar la selección. Lo cual permite una visión general sobre las características y la sustentabilidad.

Los materiales estructurales para diversos productos se pueden dividir en seis grupos: metales, cerámicos, polímeros sintéticos, los materiales orgánicos o naturales, materiales inorgánicos naturales y otros compuestos. Estos grupos abarcan probablemente más de un 99% de todos los materiales utilizados en ingenierías mecánica, civil y eléctrica. Las excepciones son las sustancias químicas como los líquidos y gases, los cuales no se comentarán aquí. Véase la tabla 2

Tabla 2 [1].

| Son presentados los seis grupos de materiales típicos para productos, así como ejemplos y aspectos para el desarrollo de productos sustentables | | | | |
|---|---|---|---|---|
| Grupo de materiales | Ejemplos | Ventajas típicas | Desventajas típicas | Clasificación de la sustentabilidad |
| Metales | Acero (Fe + C)<br>Aluminio<br>Bronce (Cu + Sn) | durables<br>fuertes<br>conformables plásticamente<br>baratos | Alto costo de maquinado<br>Sensibles a la corrosión | Fácilmente reciclables (se pueden fundir de nuevo)<br>2-3 |
| Cerámicos | Materiales sintéticos como:<br>Porcelana<br>Cristal mineral<br>Al2O3, Si3N4, SiC, etc. | no tóxicos<br>ligeros<br>duros y durables<br>resistentes a la corrosión<br>resistentes a altas temperaturas | alto costo de maquinado cuando se queman<br>quebradizos (frágiles)<br>no resistentes a cargas de tensión | Fáciles de desechar (porque no son tóxicos)<br>Se pueden fundir de nuevo, aunque es caro<br>2-3 |
| Polímeros sintéticos | Termoplásticos, como: PE, PS, PC, PP<br>Polímeros compuestos como: resina epóxica<br>Hules o gomas | no tóxicos<br>ligeros<br>baratos<br>fácil conformado<br>fácilmente reciclables mediante refundición o incineración | altamente tóxicos cuando se incineran<br>sensibles a altas temperaturas | son típicamente no renovables<br>frecuentemente son fáciles de fundir nuevamente<br>1-3 |
| Materiales Naturales orgánicos | Madera<br>Algodón<br>Seda | renovables<br>ligeros<br>baratos<br>fáciles de conformar<br>reciclables | se degradan<br>no son durables<br>son tóxicos cuando se recubren | reciclables<br>renovables<br>2-3 |
| Materiales Naturales inorgánicos | piedra<br>minerales | ¡ver cerámicos arriba! | alto costo de maquinado<br>quebradizos (frágiles)<br>no adecuados para cargas de tensión | ¡ver cerámicos arriba!<br>3 |
| Compuestos | Materiales mixtos como:<br>PS + fibra de vidrio,<br>Hule + fibras textiles,<br>asfalto,<br>compuestos (WPC) | uso optimizado de los materiales<br>frecuentemente muy fuertes y ligeros | frecuentemente su producción es cara<br>muy diversas propiedades para los diferentes compuestos | típicamente baja sustentabilidad, debido a los problemas para separar los materiales mixtos<br>1-2 |
| Notar que las ventajas, desventajas y la sustentabilidad pueden cambiar según el tipo de material específico y los ejemplos no son válidos para todos los materiales en cierto grupo.<br>"La sustentabilidad está estimada en una escala del 1 al 3, donde el 3 indica el máximo valor (o el mejor) y el 1 el peor | | | | |

*Se debe tener en cuenta que las ventajas, desventajas y la "sustentabilidad" pueden cambiar debido al tipo de material específico y también que los ejemplos no son totalmente válidos para todos los materiales presentes en un determinado grupo de materiales.*

*La sustentabilidad se estima una escala de 1 a 3, donde 3 indica el valor más alto (o mejor) para la sustentabilidad y el 1 el más bajo.*

Comentarios a la tabla 2:

Los metales: Suelen ser baratos y fáciles de reciclar en nuevos productos de refundición. Una desventaja es el peso (alta densidad), para muchos metales como el acero y aleaciones de cobre, lo que puede dar lugar a que la energía que consume durante el transporte, así como la cantidad de energía necesaria para fundir el metal sea alta, debido al alto punto de fusión típico de los metales en general. La resistencia a la corrosión del acero especialmente también es baja. La protección contra la corrosión necesita más o menos a menudo tratamientos químicos tóxicos o pinturas. El aluminio y sus aleaciones son por otro lado un ejemplo de un material muy resistentes a la corrosión de metales, que también es ligero, fuerte y fácil de reciclar, debido a un bajo punto de fusión (alrededor de 600 °C). La sustentabilidad es evaluada generalmente con las marcas de 2-3, dependiendo en, la temperatura de fusión (alta temperaturas de fusión para dar lugar alto consumo de energía para la fusión) y la toxicidad de los materiales en sí mismos o de sus procesos de extracción, por ejemplo. Los metales tóxicos, incluso en capas finas o en aleaciones suelen dar la marca de 1

Los cerámicos: Suelen ser ligeros y no tóxicos. Las materias primas en general son de arcilla para los cerámicos tradicionales y óxidos puros, nitruros y carburos para cerámicos avanzados. A menudo son no sólo muy duraderos, duros, y resistentes a la alta temperatura y a la corrosión, sino también frágiles. Los cerámicos, rara vez son reciclados en nuevos productos debido a la necesidad de trituración, molienda y refundición, lo que suele ser más costoso y que requiere más energía que la producción a partir de materia prima nueva. Los productos pueden ser re-usados, por ejemplo, pueden ser aplastados y utilizados como relleno en la construcción. La sustentabilidad es típicamente marcada con 3 para materiales basados en las arcillas naturales y 2 para los materiales que contengan componentes tóxicos o algunos cerámicos avanzadas tales como fibras, lo que podría dar mayor impacto ambiental debido al proceso de fabricación.

Los polímeros sintéticos o plásticos y caucho: Son generalmente hechos de petróleo. De todos modos, muchos polímeros se pueden hacer de materiales orgánicos naturales como la madera. Si los polímeros derivados del petróleo son reciclados mediante la quema del material entonces no es renovable, porque la cantidad de petróleo es limitada y nuevo petróleo no se formará en un tiempo corto. Muchos polímeros como el polietileno (PE) pueden ser fácilmente quemados individualmente o junto con, por ejemplo, papel durante la formación de dióxido de carbono y agua. El dióxido de carbono es inocuo en cantidades menores, pero se considera que aumenta el impacto ambiental debido al efecto invernadero en la atmósfera. Algunos polímeros, especialmente aquellos que contienen halógenos, al igual que el Teflón (PTFE) y cloruro de polivinilo (PVC) son muy perjudiciales cuando se queman debido a los humos nocivos. En este caso se recomienda la refundición. Debido a su baja temperatura de fusión de muchos polímeros termoplásticos (por lo general alrededor de 200 °C) en comparación con la de la mayoría de los metales, el consumo de energía es bastante bajo. Quema controlada de con la limpieza de los gases de escape es otra posibilidad para el reciclado. Un problema del reciclaje de plásticos es determinar de qué tipo de polímero está hecho un producto. Sin embargo, el etiquetado internacional de los polímeros ha minimizado este problema durante las últimas décadas. Plásticos termoestables y caucho son ejemplos de polímeros, que no se puede refundir lo que significa que el depósito o la utilización como material de relleno o disociación química se recomienda para su reciclado. La marcas de sustentabilidad varían entre el 1 para materiales tóxicos (por ejemplo, los polímeros que contienen halógenos) y materiales no renovables, a 3 para polímeros naturales basados en materia prima orgánica.

Materiales orgánicos naturales: Como la madera y el algodón son siempre materiales populares en diversas formas. Su reciclaje se puede hacer fácilmente en forma de energía en plantas de energía térmica para calefacción, por ejemplo. El dióxido de carbono al igual que el agua es un compuesto que está presente en estos materiales y cuando se libera al momento de quemarlos, es directamente atrapado desde el aire por un nuevo cultivo de plantas y árboles. Por lo tanto, estos materiales son típicamente renovables. Sin embargo colorear e impregnar estos materiales con otras sustancias evitan que dejen de funcionar adecuadamente, puede ser muy tóxico. Estas sustancias tóxicas causan serios impactos ambientales al ser recicladas. Por estas y otras razones más, la sustentabilidad es típicamente marcada con 3, pero en materiales impregnados, su marca puede bajar a 2 (o incluso a 1).

Materiales inorgánicos naturales: Como la piedra, roca o varios minerales son bastante similares a los cerámicos sintéticos. Por lo tanto, la típica marca de la sustentabilidad será de 3, si no existen elementos tóxicos o radiactivos involucrados.

Los materiales compuestos: Se han vuelto más y más populares en los últimos años, especialmente en forma de fibras cerámicas mezcladas con resinas plásticas. Si estos materiales pueden ser quemados como un método de reciclaje en el que no se forman sustancias tóxicas, la sustentabilidad puede ser incluso de 3, si los materiales son renovables. Sin embargo, los compuestos en general no son renovables y los problemas para separar los distintos materiales utilizados en los compuestos hacen de estos materiales en general, bastante insostenibles, lo que les da marcas de 1 ó 2 para la sustentabilidad.

De acuerdo con la Tabla 2 y las observaciones anteriores, se puede resumir que: los materiales naturales, polímeros basados en materias primas renovables, así como cerámicos y algunos metales parecen ser los materiales sustentables para el futuro. Sin embargo, el uso excesivo de la madera y el algodón dan lugar a un muy grave impacto ambiental debido a la sobreexplotación de los bosques, así como la degradación de la tierra, los problemas del agua, etc. Esto significa que un mismo material puede ser sustentable para el producto durante el uso y el reciclado, mientras que su extracción del material puede dar lugar a graves consecuencias. Los polímeros basados en el petróleo crudo deben usarse con cuidado sobre todo si no es posible reciclarlos mediante refundición. Los materiales compuestos deben utilizarse restrictivamente sobre todo tomando en cuenta los materiales que componen dicho material. También es importante tener en cuenta las posibilidades de cómo separar ciertos materiales específicos.

Capítulo 3: CASO DE ESTUDIO

Un grupo de profesores y alumnos del Centro de Diseño Mecánico e innovación tecnológica (CDMIT) realizó el rediseño de una carcasa para un lente motorizado. El lente original es producido por una empresa en California, EEUU. La carcasa original utiliza aluminio anodizado, por lo que se planteó el análisis y determinación de la carga ambiental entre ambas carcasas, la de aluminio y la rediseñada por el CDMIT en ABS.

Se compararán las carcasas hechas de aluminio anodizado y de ABS, para saber cuál es la que menos carga ecológica provoca y así saber cuál es la menos perjudicial para el medio ambiente según este criterio y se seguirá la secuencia mostrada en la figura 7. La carcasa del lente motorizado se muestra en la figura 8.

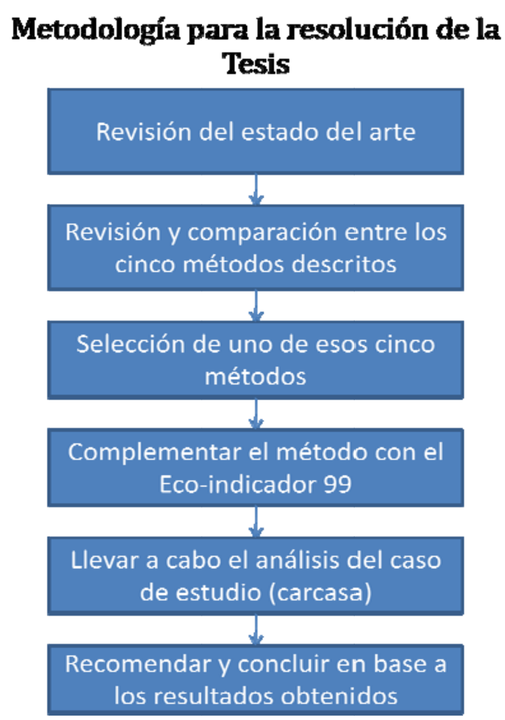
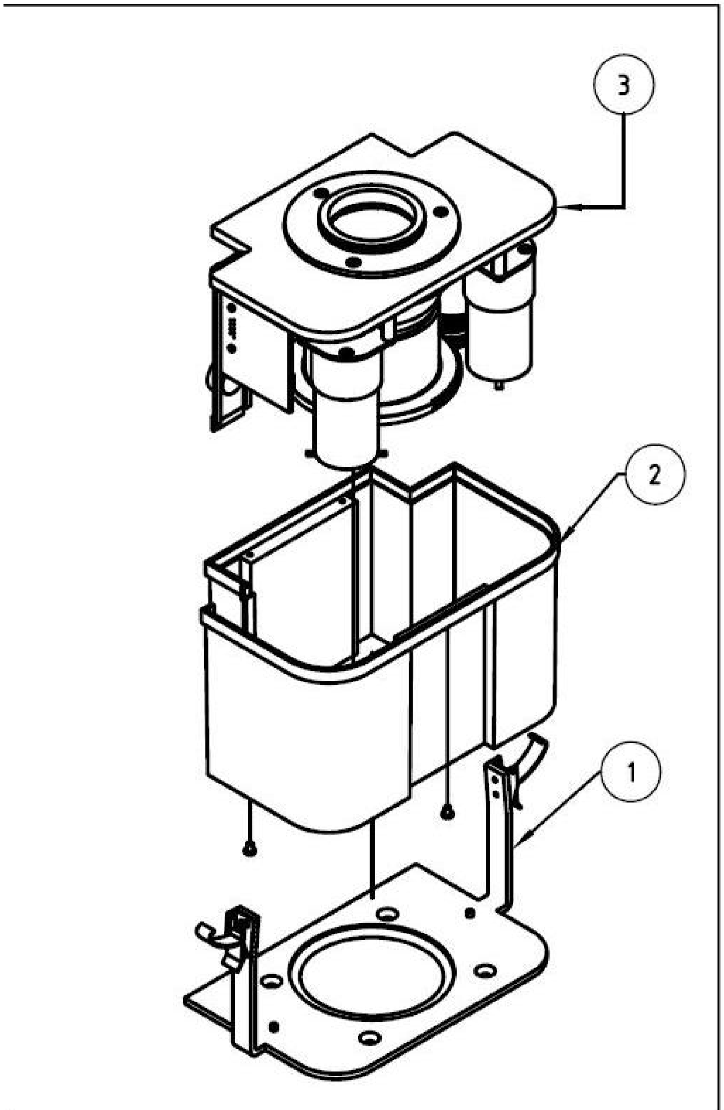



Fig. 7 Metodología para la resolución de la Tesis




| Id | Nombre | Ctd | Referencia |
|---|---|---|---|
| 3 | HEAD | 1 | 28_100_B |
| 2 | CHASIS | 1 | 28_200_B |
| 1 | PLATFORM | 1 | 28_300_B |

| | | |
|---|---|---|
| MECHATRONIC INSTRUMENTATION | | Fecha: 18/04/07<br>Mat: NA |
| Todos los derechos sobre la informaqción contenida en este plano son propiedad exclusiva y legal de IDITEC S.A. de C.V. queda tottamente prohibida su reproducción total o parcial. | Elaboró: ECR | Acadado: NA<br>Esc.: SE · Acot.: mm |
| Revisó: ECR | Aprobó: MLP | Cantidad: 1 unidad |
| Título: *LENTE 28 MM* *Arreglo general* | ANSI A | Nº de Dib.: 28_000_B |

Figura 8. *El número 2 es el componente a analizar (Chasis o carcasa)*

Es importante considerar el ciclo de vida del producto para llevar a cabo los cálculos que ayudarán a concluir que material es que más conviene para la manufactura de la carcasa, con el objetivo de que sea más sustentable. Y este es presentado en el diagrama 1.

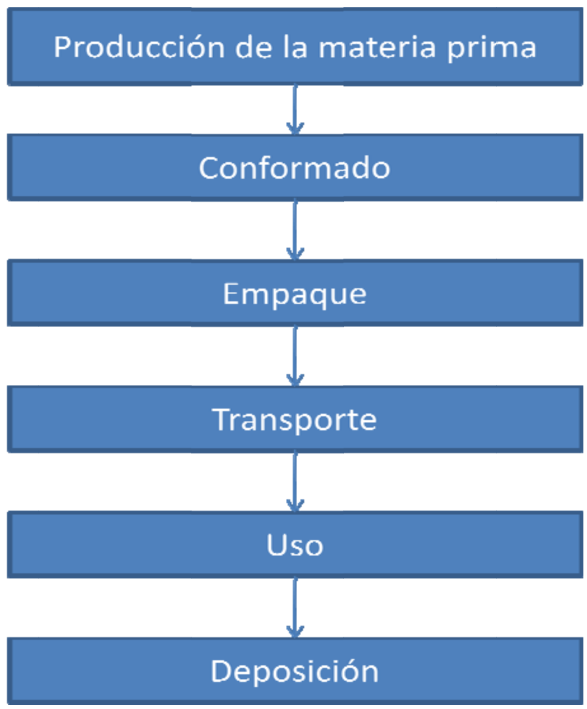



*Diagrama 1 que presenta el ciclo de vida de la carcasa, sin importar que sea de aluminio o de ABS.*

¿Cómo ocupar el Eco-indicador 99?

La medición se realizó de la siguiente manera:

- Primero se obtuvieron algunas propiedades de la carcasa tanto de aluminio como de ABS, tales como densidad, volumen, masa, etcétera, para poder ocupar el Eco-indicador 99.

- Después se buscó el indicador del material en las tablas del Manual del Eco- indicador 99 [13].
- Y por último se propusieron escenarios posibles de cómo se pudo haber realizado cada etapa del ciclo de vida.

Para mayores detalles de cómo se ocupa el Eco-indicador 99, se puede revisar el ejemplo que contiene el manual [13].

Empleo del método

Como se mencionó, el estudio del caso consistirá en crear escenarios para cada etapa del ciclo de vida y cada material por analizar. Para encontrar la manera más amigable con el medio ambiente de crear el componente.

La fig. 9 presenta un esquema realizado en Autocad con las dimensiones principales de la carcasa

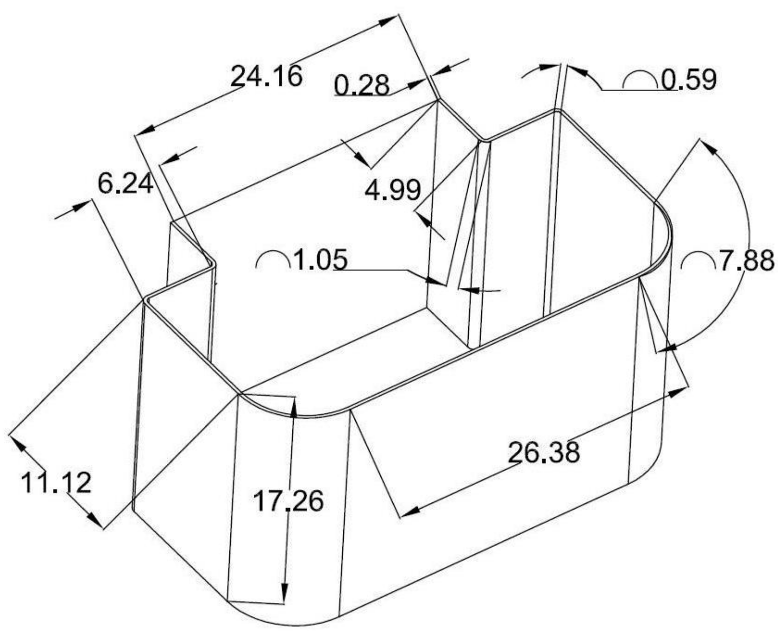



*Fig. 9*

*Dimensiones de la carcasa en* [cm].

En la figura 9 se ven las medidas sacadas del diagrama y con las cuales se obtuvo el volumen de la pieza, cabe aclarar que se aplicó un método indirecto. Se modelo como una placa plana doblada y del mismo grosor en todos los puntos del cuerpo, es decir el producto del perímetro (perímetro exterior) (prácticamente igual al perímetro interior) por el grosor y por la altura. Por lo tanto el volumen arrastra un error no significativo para los fines de este trabajo, que afecta de igual manera para los 2 materiales a comprar.

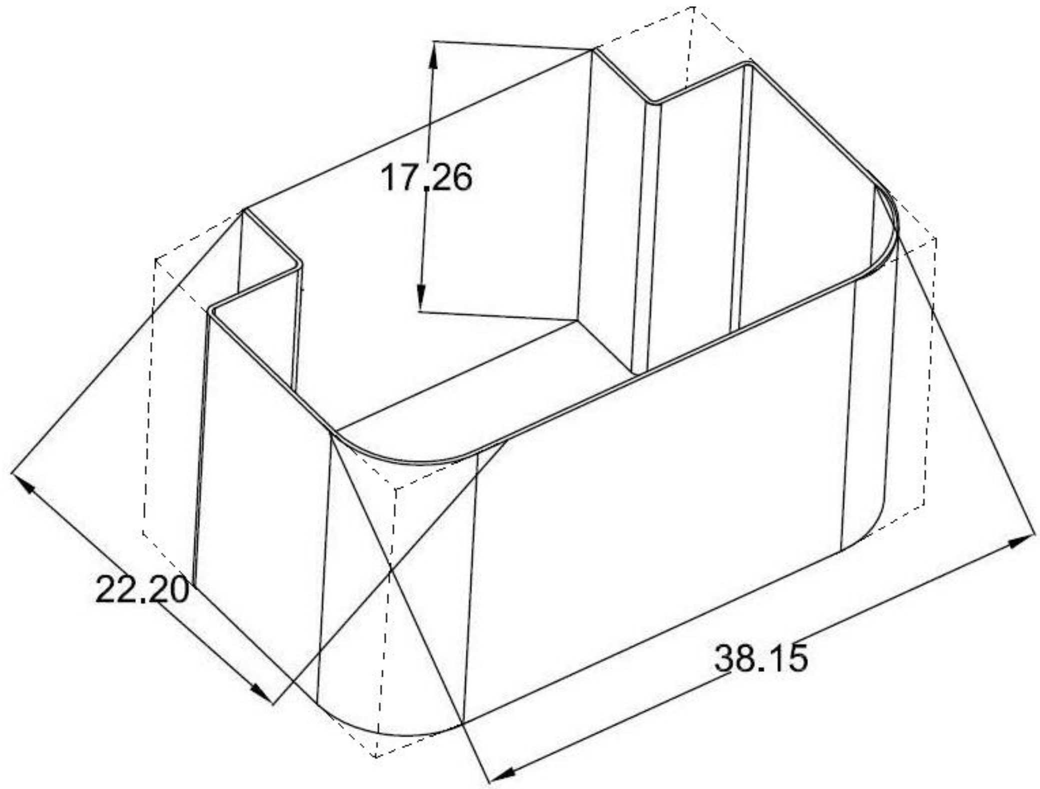
De donde se obtiene que: Volumen = 552.3 [$m^3$] es igual para ambos casos.

Ahora bien, la herramienta exige para usar las tablas la masa del producto y el material del que esta hecho, por lo que se sacaron las siguientes cantidades.

Para aluminio:
Densidad = 2698.4 [$kg/m^3$]; de donde se obtiene la masa.
Masa = 1.49 [kg]

Para ABS
Densidad = 1050 [$kg/m^3$]; de donde se obtiene la masa.
Masa = 0.58 [kg]

Otra medida que se necesita para la aplicación de algunos indicadores el “volumen cúbico”, esto quiere decir el volumen mínimo del prisma que contendría al chasis en su interior, para ejemplificar esta propiedad ver la figura 10.




*La figura 10 representa en el volumen cúbico, (acotaciones en* [cm]).

Con los cálculos correspondientes alcanzamos el volumen cúbico de = 14,618.0118 [$cm^3$].

Una vez obtenidos los valores anteriores de las propiedades ya se puede proceder a aplicar el EI99 para ambos materiales a comparar.

## Carcasa o chasis de aluminio anodizado

**Etapa de producción de materia prima.**

Aquí existen 2 posibilidades medibles, las cuales son:

- Aluminio 100% reciclado, que se refiere que la materia prima se obtiene de aluminio reciclado. Y que tiene un indicador de 60 [mp/kg] [13].
- Aluminio 0% reciclado, que se refiere al aluminio obtenido directamente del mineral. Y que tiene un indicador de 780 [mp/kg] [13].

**Etapa de conformado de la carcasa.**

Esta etapa se dividirá en 2 para el caso del aluminio, la primera será la parte de manufactura de la carcasa y la segunda será la parte del tratamiento, en este caso el anodizado.

Las opciones para la parte de manufactura de la carcasa son:

- Producción de lámina desde el bloque (o lingote), con un indicador de 30 [mp/kg] [13].
- Doblado de aluminio, con un indicador de 0.000047 [mp] [13].
- Soldadura de puntos de aluminio, con un indicador de 2.7 [mp/PS] [13]. Donde PS es un punto de soldadura de 7 [mm] de diámetro.
- Extrusión de aluminio, con un indicador de 72 [mp/kg] [13].
- Maquinado, con un indicador de 800 [mp/dm$^3$] [13], unidad por volumen retirado.

Para el caso del maquinado el volumen retirado será el volumen cúbico menos el volumen de la carcasa, por lo tanto el volumen retirado será: Vr = 14065.7118 [cm$^3$] ó 14.0657118 [dm$^3$].

En esta etapa cabe señalar que si se realiza por maquinado o extrusión, entonces sólo se ocupa un proceso, ya que se podría realizar directo de un bloque o lingote, sin embargo los otros 3 se ocupan juntos es decir que de un bloque o lingote se necesita producir una lámina, luego doblarla y después soldarla. Por lo que esos efectos se suman

**Anodizado de la carcasa.**

Anodizado: es el proceso mediante el cual se protege al aluminio contra la corrosión del medio donde se encuentra. Luego del conformado, este metal (por lo general) entra en contacto con el aire y forma por si solo una delgada capa de película de óxido con un espesor aproximado de 0.01 [µm] la cual tiene algunas propiedades protectoras, que sin embargo en algunas ocasiones son insuficientes. El proceso de anodizado consiste en obtener de manera artificial una capa de óxido de mayor espesor y con mejores características de protección, mediante la electrólisis del aluminio en un medio ácido, y esto no es otra cosa mas que sumergir la pieza de aluminio en un medio ácido y aplicar electricidad. Así se obtienen capas que oscilan entre los 25 y 30 [µm] en los tratamientos de protección o decoración (ya que también sirve para colorear al aluminio sin necesidad de usar pintura) y llegan a ser de hasta 100 µm para tratamientos de endurecimiento superficial (anodizado duro) [14].

El medio ácido usado por lo general en este proceso es el ácido sulfúrico $H_2SO_4$ al 20% en agua [14].

Con lo anterior estamos en posibilidad de aplicar el eco-indicador 99:

Las opciones para el anodizado son:

Primera: Estimar el indicador aproximándolo por un galvanizado electrolítico con un valor en el EI99 de 130 [mp/$m^2$] [13].

Para esta opción la superficie será tomada como la multiplicación del perímetro del chasis por su altura, por lo tanto el área es:

A = 1972.4728 [$cm^2$] ó 0.19725 [$m^2$].

La otra opción es tomar en cuenta las sustancias que se ocupan para el anodizado, aunque es más compleja y menos confiable por qué no aparece en las tablas del EI99. Sin embargo se hace de la siguiente manera:

La sustancia que se ocupa generalmente para este proceso es el ácido sulfúrico y buscando en la literatura se encontró el valor idóneo de concentración para el proceso de anodizado de 20% en agua [14].

También se necesitan los valores de la energía eléctrica usada ya que es un proceso electrolítico.

| Superficie | Temperatura del medio | Tiempo | Voltaje | Amperaje |
|---|---|---|---|---|
| 63 $cm^2$ | 30 °C | 30 min. | 11 V | 2.7 A |
| 95 $cm^2$ | 13 °C | 25 min. | 14 V | 2.3 A |
| 114 $cm^2$ | 20 °C | 40 min. | 13 V | 3.45 A |
| 168 $cm^2$ | 21 °C | 60 min. | 11 V | 5.6 A |

*Tabla 3 donde se muestran valores para el anodizado [15].*

De esta tabla se pueden obtener los valores para ocupar el indicador de electricidad que contiene el EI99.

Quedando entonces que los indicadores son:

Para el ácido sulfúrico, 22 [mp/kg] [13].

Para la electricidad, 26 [mp/kWh] [13].

Otros valores que se requieren son:

*Masa del ácido sulfúrico* necesaria para las características de esta pieza. Como se dijo anteriormente el ácido tiene un 20% de concentración en agua. Si se considera un volumen de solución mínimo para llevar acabo la electrólisis de 1.4 veces el volumen cúbico del chasis (anteriormente definido) entonces el volumen de la solución sería $V_s$ = 20,465.21652 [$cm^3$], el cual se podría redondear a 20 [$dm^3$] ó 20 litros para simplificar el cálculo, por lo cual el 20% = 4 litros, y sabemos que la densidad del ácido sulfúrico es de 1,800 [$kg/m^3$], entonces la masa requerida de ácido sulfúrico es de 7.2 [kg].

Cantidad de Energía eléctrica necesaria para llevar a cabo la electrólisis, dada en kWh.

Para lo cual se ocupará la tabla anterior, que cabe mencionar que no es del todo exacto en la medida de superficie pero de cualquier modo se ocuparán los valores del siguiente renglón, tomando en consideración que son los más cercanos, debido al valor calculado de superficie:

| | | | | |
|---|---|---|---|---|
| 168 $cm^2$ | 21 °C | 60 min. | 11 V | 5.6 A |

Por lo cual la energía necesaria para llevar a cabo la electrólisis para el anodizado es: E = (11V)*(5.6A)*(1hr.) = 61.6 [Wh] = 0.0616 [kWh]

**Empacado**

Dado que el EI99 sólo tiene 5 materiales considerados para empaque y únicamente el cartón es viable para empacar este componente, pues sólo se tomará en cuenta este.

Quedando el indicador:

- Cartón para empacar: 69 [mp/kg] [13].

- Sin empaque: 0

Para poder sacar la masa unitaria para empaque de las carcasas, se va usar un concepto llamado gramaje que se refiere a la masa por unidad de área y que oscila entre 160 a 600 [g/m$^2$] [16]. Para esto se usará  la superficie del prisma envolvente del chasis de la figura 10 que tiene una superficie de 0.3777 [m$^2$] y se usará el valor máximo de gramaje en este caso 600 [g/m$^2$] así se obtiene una masa de 226.63 gramos ó 0.22663 [kg].

**Distribución**

Esta etapa es donde más variedad existe para escoger y he aquí que las opciones que presenta el EI99.

Los indicadores son:

- Camioneta de distribución <3.5 ton y con un promedio de 33% de carga: 140 [mp/ton.km] [13].
- Camión 16 ton cargado al 40%: 34 [mp/ton.km] [13].
- Camión 28 ton cargado al 40%: 22 [mp/ton.km] [13].
- Camión 28 ton. (volumen): 8 [mp/m$^3$.km] [13]. se usa cuando el volumen es el factor determinante en lugar de la carga.

- Camión 40 ton cargado al 50%: 15 [mp/ton.km] [13].
- Automóvil: 29 [mp/km] [13].
- Transporte ferroviario considerando 20% de trenes a diesel y 80% de trenes eléctricos (promedio europeo): 3.9 [mp/ton.km] [13].
- Carguero interior cargado al 70%: 5.1 [mp/ton.km] [13].
- Carguero Oceánico cargado al 70%: 1.1 [mp/ton.km] [13].
- Transporte Aéreo promedio cargado al 78%: 78 [mp/ton.km] [13].
- Transporte Aéreo continental Boeing 737 cargado al 62%: 120 [mp/ton.km] [13].
- Transporte Aéreo Intercontinental Boeing 747 cargado 78%: 80 [mp/ton.km] [13].
- Transporte Aéreo Intercontinental Boeing 767 cargado al 71%: 72 [mp/ton.km] [13].

Para el caso del transporte se aplicarán los indicadores de tal forma queden únicamente en unidades de mili puntos. Ya que dependerá de la necesidad y la capacidad del productor, el transporte que se elija.

**Uso**

En este caso no se le va dar ningún indicador a esta etapa ya que como se trata de un chasis que sirve para cubrir un lente fotográfico y por lo tanto el uso que se le puede dar es muy variado, pero difícilmente causará un impacto ecológico apreciable, aunque no se descarta del todo que, en efecto, pueda impactar de algún modo al ambiente.

**Deposición**

Esta etapa se refiere al momento en que por cualquier motivo el usuario decide deshacerse del componente y “lo tira a la basura”.

Los indicadores son:

- Si se recicla el aluminio: -720 [mp/kg] [13].

Ahora, si se trata el desperdicio se cuenta con los siguientes indicadores.

- Por incineración: -110 [mp/kg] [13].
- Por relleno sanitario: 1.4 [mp/kg] [13].
- Mediante el sistema municipal (aclarando que se trata de estándares europeos, y sólo sirve para aluminio primario, es decir aquel que sale directo del mineral): -23 [mp/kg] [13].

Una vez definidas las opciones que existen en cada etapa del ciclo de vida, ahora se plantearán los distintos escenarios y se escogerá el mejor en términos de carga ecológica.

<table>
<tr><th colspan="7">Carcasa de Aluminio Anodizado</th></tr>
<tr><th>etapa</th><th>subetapa</th><th>opción</th><th>cantidad</th><th>indicador</th><th>suma de efectos</th><th>resultado</th></tr>
<tr><td rowspan="2">etapa de producción de materia prima</td><td rowspan="2"></td><td>aluminio reciclado</td><td>1.49 kg</td><td>60 mp/kg</td><td>N.A.</td><td>89.4 mp</td></tr>
<tr><td>aluminio primario</td><td>1.49 kg</td><td>780 mp/kg</td><td>N.A.</td><td>1162.2 mp</td></tr>
<tr><td rowspan="5">etapa de conformado</td><td rowspan="5">etapa de manufactura del chasis</td><td>producción de lámina</td><td>1.49 kg</td><td>30 mp/kg</td><td rowspan="3">44.7 mp + 0.000047 mp + 21.6 mp =</td><td rowspan="3">66.300047 mp</td></tr>
<tr><td>doblado de aluminio</td><td>N.A.</td><td>0.000047 mp</td></tr>
<tr><td>soldadura de puntos</td><td>8 PS</td><td>2.7 mp/PS</td></tr>
<tr><td>extrusión</td><td>1.49 kg</td><td>72 mp/kg</td><td>N.A.</td><td>107.28 mp</td></tr>
<tr><td>maquinado</td><td>14.0657 $dm^3$</td><td>800 $mp/dm^3$</td><td>N.A.</td><td>11252.57 mp</td></tr>
<tr><td rowspan="3"></td><td rowspan="3">etapa del anodizado</td><td>galvanizado</td><td>0.19725 $m^2$</td><td>130 $mp/m^2$</td><td>N.A.</td><td>25.64 mp</td></tr>
<tr><td>$H_2SO_4$</td><td>7.2 kg</td><td>22 mp/kg</td><td rowspan="2">158.4 mp + 1.6016 mp =</td><td rowspan="2">160 mp</td></tr>
<tr><td>Energía eléctrica</td><td>0.0616 kWh</td><td>26 mp/kWh</td></tr>
<tr><td rowspan="2">etapa de empaque</td><td rowspan="2"></td><td>cartón</td><td>0.22663 kg</td><td>69 mp/kg</td><td>N.A.</td><td>15.64 mp</td></tr>
<tr><td>nada</td><td>N.A.</td><td>0 mp</td><td>N.A.</td><td>0 mp</td></tr>
<tr><td rowspan="3">etapa de transporte</td><td rowspan="3"></td><td>Camioneta de distribución <3.5 ton</td><td rowspan="3">1.49 toneladas y 1 km</td><td>140 mp/ton.km</td><td>N.A.</td><td>208.6 mp</td></tr>
<tr><td>Camión 16 ton</td><td>34 mp/ton.km</td><td>N.A.</td><td>50.66 mp</td></tr>
<tr><td>Camión 28 ton .</td><td>22 mp/ton.km</td><td>N.A.</td><td>32.78 mp</td></tr>
</table>

| | | | | | | |
|---|---|---|---|---|---|---|
| | | Camión 28 ton. (volumen) | 1 m3 y 1 kg | 8 mp/m3.km | N.A. | 8 mp |
| | | Camión 40 ton | 1.49 toneladas y 1 km | 15 mp/ton.km | N.A. | 22.35 mp |
| | | Transporte ferroviario (promedio europeo) | | 3.9 mp/ton.km | N.A. | 5.811 mp |
| | | Carguero interior | | 5.1 mp/ton.km | N.A. | 7.6 mp |
| | | Carguero Oceánico | | 1.1 mp/ton.km | N.A. | 1.64 mp |
| | | Transporte Aéreo promedio | | 78 mp/ton.km | N.A. | 116.22 mp |
| | | Transporte Aéreo continental | | 120 mp/ton.km | N.A. | 178.8 mp |
| | | Transporte Aéreo Intercontinental. | | 80 mp/ton.km | N.A. | 119.2 mp |
| | | Transporte Aéreo Intercontinental | | 72 mp/ton.km | N.A. | 107.28 mp |
| etapa de deposición | reciclaje | aluminio reciclado | 1.49 kg | - 720 mp/kg | N.A. | - 1072.8 mp |
| | tratamiento del desperdicio | por incineración | 1.49 kg | - 110 mp/kg | N.A. | - 163.9 mp |
| | | en relleno sanitario | 1.49 kg | 1.4 mp/kg | N.A. | 2.086 mp |
| | | sistema municipal | 1.49 kg | _- 23 mp/kg | N.A. | - 34.27 mp |

La multiplicación de 2 posibilidades en la etapa de producción de materia prima, por 3 en la etapa de conformado en la subetapas de manufactura del chasis, por 2 en la etapa de conformada en la subetapas de anodizado, por 2 en la de empaque, por 12 en la de transporte, por 4 en la deposición, arrojan un total de 1152 combinaciones diferentes equivalentes a los escenarios posibles para este material. En la tabla se ve como se usan los indicadores, siendo los verdes los que representan el escenario ideal para la carcasa de aluminio durante su ciclo de vida.

Quedando como total del escenario ideal: ***T = - 869.11 [mp].***

## Carcasa o chasis de ABS

**Etapa de producción de materia prima.**

- Producción de ABS con un indicador de: 400 [mp/kg] [13].

**Etapa de conformado.**

Las opciones para la parte de manufactura de la carcasa son:

- Inyección, con un indicador de 21[mp/kg] [13].
- Maquinado, con un indicador de 6.4 [mp/dm$^3$] [13], unidad por volumen retirado.

Para el caso del maquinado el volumen retirado será, al igual que en el caso del aluminio, el volumen cúbico menos el volumen de la carcasa, por lo tanto el volumen retirado será: Vr = 14065.7118 [cm$^3$] ó 14.0657118 [dm$^3$].

**Etapa de Empaque**

Para esta etapa se considera lo mismo que para el caso de la carcasa de aluminio.

Quedando el indicador:
Cartón para empacar: 69 [mp/kg] [13].
Sin empaque: 0

**Etapa de transporte**

Esta etapa al igual que la anterior, toma en cuenta las mismas consideraciones que en el caso de la carcasa de aluminio.

Los indicadores son:

- Camioneta de distribución <3.5 ton y con un promedio de 33% de carga: 140 [mp/ton.km] [13].
- Camión 16 ton cargado al 40%: 34 [mp/ton.km] [13].
- Camión 28 ton cargado al 40%: 22 [mp/ton.km] [13].
- Camión 28 ton. (volumen): 8 [mp/m$^3$.km] [13]. se usa cuando el volumen es el factor determinante en lugar de la carga.
- Camión 40 ton cargado al 50%: 15 [mp/ton.km] [13].
- Automóvil: 29 [mp/km] [13].
- Transporte ferroviario considerando 20% de trenes a diesel y 80% de trenes eléctricos (promedio europeo): 3.9 [mp/ton.km] [13].
- Carguero interior cargado al 70%: 5.1 [mp/ton.km] [13].
- Carguero Oceánico cargado al 70%: 1.1 [mp/ton.km] [13].
- Transporte Aéreo promedio cargado al 78%: 78 [mp/ton.km] [13].
- Transporte Aéreo continental Boeing 737 cargado al 62%: 120 [mp/ton.km] [13].
- Transporte Aéreo Intercontinental Boeing 747 cargado 78%: 80 [mp/ton.km] [13].
- Transporte Aéreo Intercontinental Boeing 767 cargado al 71%: 72 [mp/ton.km] [13].

Para el caso del transporte se aplicarán los indicadores de tal forma queden únicamente en unidades de mili puntos. Ya que dependerá de la necesidad y la capacidad del productor, el transporte que se elija.

A diferencia de la carcasa de aluminio se tomará en cuenta un peso de 0.5799 toneladas ya que la proporción es de 1.49 a 0.5799, ya que esa es la relación en peso unitario.

**Etapa de Uso**

En este caso al igual que para la carcasa de aluminio no se le dará ningún indicador.

**Etapa de deposición**

Esta etapa se refiere al momento en que por cualquier motivo el usuario decide deshacerse del componente y “lo tira a la basura”.

Aquí hay que hacer una consideración importante, ya que para el ABS no existe indicador propio, en algunos casos se menciona en las tablas del EI99 que se puede ocupar el indicador del poliestireno, así que se ocupará para todos los casos el indicador del poliestireno, tomando en cuenta que los 2 son termoplásticos y que el ABS es Acrilonitrilo Butadieno Estireno con una estructura que contiene la molécula del Estireno y por lo tanto al ser el poliestireno el plástico más similar al ABS por eso se usarán los indicadores para la carcasa hecha de este último material. En las figuras 11 y 12 se ven las moléculas que conforman cada uno de los 2 materiales.

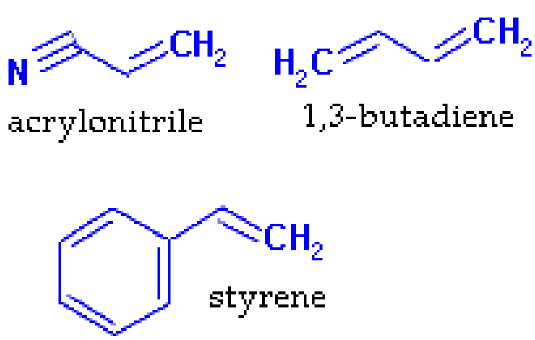



*Figura 11 muestra las moléculas del ABS.*

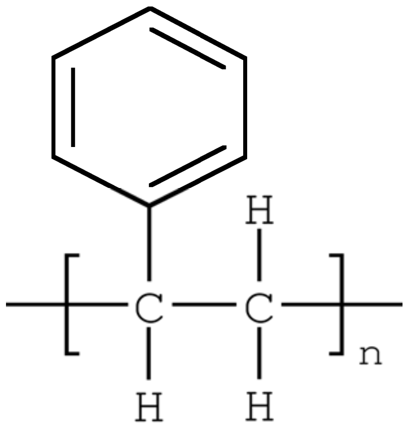


*Figura 12 muestra molécula del poliestireno.*

Los indicadores son:

- Si se recicla el ABS: -240 [mp/kg] [13].

Ahora, si se trata el desperdicio se cuenta con los siguientes indicadores.

- Por incineración: -5.3 [mp/kg] [13].
- Por relleno sanitario: 4.1 [mp/kg] [13].
- Mediante el sistema municipal (aclarando que se trata de estándares europeos, y sólo sirve para aluminio primario, es decir aquel que sale directo del mineral): 2 [mp/kg] [13].

Una vez definidas las opciones que existen en cada etapa del ciclo de vida, ahora se plantearán los distintos escenarios y se escogerá el mejor en términos de carga ecológica.

| Carcasa de ABS | | | | | |
|---|---|---|---|---|---|
| **etapa** | **subetapa** | **opción** | **cantidad** | **indicador** | **resultado** |
| etapa de producción de materia prima | | producción de ABS | 0.5799 kg | 400 mp/kg | 231.96 mp |

| | | | | | |
|---|---|---|---|---|---|
| etapa de conformado | | inyección | 0.5799 kg | 21 mp/kg | 12.18 mp |
| | | maquinado | 14.0657 dm3 | 6.4 mp/dm3 | 90.0205 mp |
| etapa de empaque | | cartón | 0.22663 kg | 69 mp/kg | 15.64 mp |
| | | nada | N.A. | 0 mp | 0 mp |
| etapa de transporte | | Camioneta de distribución <3.5 ton | 0.5799 toneladas y 1 km | 140 mp/ton.km | 81.186 mp |
| | | Camión 16 ton | | 34 mp/ton.km | 19.7166 mp |
| | | Camión 28 ton . | | 22 mp/ton.km | 12.7578 mp |
| | | Camión 28 ton. (volumen) | 1 m3 y 1 kg | 8 mp/m3.km | 8 mp |
| | | Camión 40 ton | 0.5799 toneladas y 1 km | 15 mp/ton.km | 8.6985 mp |
| | | Transporte ferroviario (promedio europeo) | | 3.9 mp/ton.km | 2.26161 mp |
| | | Carguero interior | | 5.1 mp/ton.km | 2.95749 mp |
| | | Carguero Oceánico | | 1.1 mp/ton.km | 0.63789 mp |
| | | Transporte Aéreo promedio | | 78 mp/ton.km | 45.2322 mp |
| | | Transporte Aéreo continental | | 120 mp/ton.km | 69.588 mp |
| | | Transporte Aéreo Intercontinental . | | 80 mp/ton.km | 46.392 mp |
| | | Transporte Aéreo Intercontinental | | 72 mp/ton.km | 41.7528 mp |
| etapa de deposición | reciclaje | reciclado de poliestireno | 0.5799 kg | _240 mp/kg | _139.176 mp |
| | tratamiento del desperdicio | por incineración | 0.5799 kg | _5.3 mp/kg | _3.07347 mp |
| | | en relleno sanitario | 0.5799 kg | 4.1 mp/kg | 2.3776 mp |
| | | sistema municipal | 0.5799 kg | 2 mp/kg | 1.1598 mp |

La multiplicación de una posibilidad en la etapa de producción de materia prima, por 2 en la de conformado, por 2 en la de empaque, por 12 en la de transporte, por 4 en la deposición, arrojan un total de 192 combinaciones diferentes equivalentes a los escenarios posibles para este material. En la tabla se ve como se usan los indicadores, siendo los verdes los que representan el escenario ideal para la carcasa de aluminio durante su ciclo de vida.

Quedando como total del escenario ideal: ***T = 113.66 [mp]***

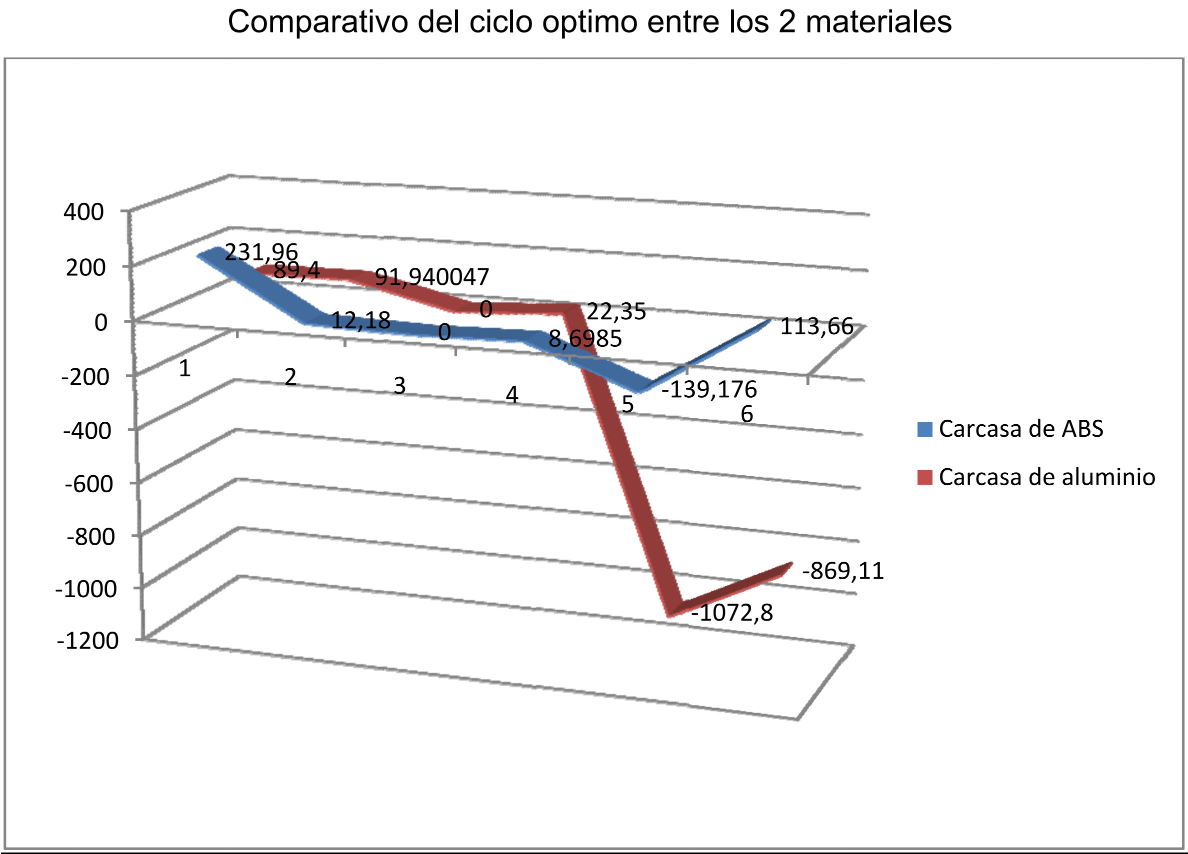



*Fig. 13: En está gráfica se ve el comportamiento del eco-indicador en cada etapa del ciclo de vida de la carcasa para los 2 materiales. Los números que se ven en el eje horizontal son los que corresponden a las etapas del ciclo de vida del producto: 1) etapa de producción de materia prima, 2)etapa de conformado, 3) empaque, 4) trasporte, 5) deposición y 6) eco-indicador del ciclo completo.*

CAPÍTULO 4: RECOMENDACIONES Y CUESTIONES IMPORTANTES A TOMAR EN CUENTA.

**Recomendaciones**

- Que la carcasa se haga de aluminio, siempre y cuando sea reciclado de donde se toma y reciclado al final de su ciclo de vida.
- Evaluar para efectos de funcionalidad y estética que tan importante sería el anodizado para el aluminio.
- Para la realización del diseño, integrar el resultado obtenido en este estudio, dentro de las consideraciones que se hagan para la selección de material.
- No tomar el resultado de este estudio como un valor de sustentabilidad, sino como un valor de carga ecológica al cual se le tienen que integrar aspectos sociales y económicos para determinar un valor de sustentabilidad.

**Consideraciones importantes a tomar en cuenta**

Estos indicadores se hicieron para Europa, seguramente algunos valores variarán para el caso de México, sin embargo el manual del eco-indicador 99 [13] indica que para hacer nuevos indicadores con características especiales se necesita ya sea un software apropiado de evaluación del ciclo de vida, o bien obtener actualizaciones de los indicadores registrándose en la página [12], y ambas cuestiones están fuera de los objetivos y alcances de esta Tesis.

Para el aluminio

Se necesita identificar o calcular de forma exacta los indicadores correspondientes pues en la etapa del anodizado para la forma en que se obtuvieron los indicadores no es del todo exacta, ya que no hay un indicador hecho ex profeso para el tratamiento del anodizado, pues se tuvo que aproximar de alguna manera y siendo el galvanizado el tratamiento más similar al anodizado, dado que los dos involucran soluciones en las que se sumerge una pieza para llevar a cabo la electrólisis, por eso se eligió como la forma más adecuada de aproximarse al fenómeno real.

La otra manera en que se estimó fue hecha sólo para mencionar como se podrían tomar en cuenta los procesos por los cuales se lleva a cabo el tratamiento, sin embargo los datos no se consideran del todo fidedignos por lo que sólo se menciona. Aunque no es una forma adecuada de aproximarse al fenómeno ya que además hay que considerar que se hizo este eco-indicador tomando en cuenta que el baño en la solución sólo se hace en una pieza una sola vez y no es lo que realmente se hace en la industria.

**Para el ABS**

En la etapa de deposición como ya se dijo anteriormente no se trata de un indicador hecho para el ABS sino para el poliestireno no espumoso, cabe aclarar, por lo que queda a consideración de quien use el EI99 su uso para aplicarlo al ABS, sobre todo para los casos de reciclaje y de tratamiento del desperdicio en el sistema municipal, que son los que no indican si se puede utilizar para el ABS.

**Para ambos materiales**

En la etapa de empaque obviamente se toma como la mejor opción el no tener empaque ya que así se pude ahorrar carga ecológica en esta etapa, pero en caso de ser totalmente necesario tener al componente empacado, sólo se necesita sumar el indicador del empaque al resultado total.

En la etapa de transporte se eligió el camión de 40 toneladas como la carga ideal ya que en México gran parte de la producción industrial se mueve por carretera en camiones, además de que el indicador del trasporte ferroviario esta hecho tomando en cuenta las condiciones de Europa que claramente son muy distintas de las de México, cosa que no es tan evidentemente diferente para los trasportes terrestres como los camiones, aunque los de Europa tal vez sean más nuevos y menos contaminantes, por lo que el valor del eco-indicador variará para el caso mexicano. Así que por eso en esta etapa no se escogió el que tiene menor indicador sino el más relacionado con la realidad del país. Cabe aclarar que se si para un análisis distinto se necesita tomar en cuenta una distancia, peso o tipo de trasporte distinto, sólo se necesitan cambiar los valores en la tabla por los nuevos y hacer la suma del indicador nuevo al resultado total.

CAPÍTULO 5: CONCLUSIONES

## Conclusiones

1) Después de hacer el análisis se cumplió el objetivo y se determina que el aluminio es la mejor opción para hacer la carcasa de este lente motorizado, si y sólo si se recicla, porque hay una variación en los valores de las tablas, sobre todo en las etapas de producción de materia prima y de deposición, esto se presume aún a pesar de estar trabajando con los indicadores europeos ya que supongo que los valores modificados para el caso mexicano no variarían lo suficiente para que el ABS fuera la mejor opción.

La Hipótesis queda comprobada, porque entonces uno de los 2 materiales, dependiendo del reciclado resultará ser el más atractivo que el otro desde el punto de vista ecológico,

2) Esto no quiere decir que la estimación de carga ecológica sea el factor determinante para seleccionar este material, Hay muchos aspectos a considerar, como pueden ser: propiedades mecánicas, propiedades eléctricas, propiedades térmicas, costo, etc. Sin embargo la ecología no se había integrado a esta lista de consideraciones hasta fechas recientes y en la mayoría de las ocasiones únicamente con métodos cualitativos, sin un respaldo metodológico que arrojará valores numéricos de comparación, es por esto que el análisis hecho en este ejercicio es un paso adelante en este tipo de estudios.

Una de las dificultades que encuentran los ingenieros y demás profesionales de diseño para incluir la carga ecológica como una parte del análisis, es la dificultad de medirla o estimarla.

Medir es una herramienta para la reflexión, y la reflexión es la clave para el continuo aprendizaje. La información que reunimos por medio del proceso de medición ayuda a entender la conexión entre las actividades que realizamos y nuestras metas. El medir nos permite probar las suposiciones que todos hacemos acerca de cómo funcionan las cosas. Si encontramos que nuestras suposiciones son incorrectas, que muchas veces lo son, por medio de la medición podemos obtener nuevas ideas acerca de lo que es correcto para nuestra causa y así ayudar con esta investigación o descubrimiento a nuestra comunidad. Después podemos volver a enfocar nuestras actividades para asegurarnos que podemos lograr nuestras metas.

Esto fue lo que pasó durante el desarrollo del caso de estudio de esta Tesis, que es un caso real, ya que mi primera suposición fue que el ABS cumpliría con ser el mejor material en términos de ecología, como lo fue en términos de funcionalidad. Sin embargo después de estimar la carga ecológica de todo el ciclo de vida resultó que el aluminio fue el mejor. Esto se debe principalmente a que en las suposiciones que se regularmente se hacen antes de medir, no se incluye las etapas de producción de materia prima y de deposición del producto cuando ya no es útil. Fue en estas etapas donde el aluminio resultó ser mejor que el ABS.

3) Ya se mencionó la importancia de medir, y también se dijo que la mejor herramienta que se encontró para hacerlo fue el Eco-indicador 99. Sin embargo no es una herramienta perfecta y se encontraron algunas deficiencias o carencias, y esto sólo demuestra que tan nuevo es el concepto de Eco-diseño.

Algunas de estas carencias son:

Faltan en las tablas del manual del EI99 aspectos que son cotidianos de ingeniería como tratamientos, por ejemplo: el anodizado, procesos de manufactura, como por ejemplo la extrusión de plásticos o el roto moldeo.

También en la página 10 del manual del EI99 [13] se puede ver que dentro de la etapa de producción de materias primas se toman en cuenta aspectos como la extracción, procesos de refinamiento o enriquecimiento, sin embargo deja fuera aspectos como maquinaria para llevar a cabo dichos procesos o infraestructura como almacenes, y lo mismo pasa en etapas posteriores que no incluyen los bienes capitales, así que en ese aspecto el EI99 le falta cierta exactitud. Pero en el balance creo que con este análisis se llegó a buen puerto, pues la herramienta condiciona que tan profundo se puede hacer.

4) La gravedad de las consecuencias del deterioro del medio ambiente cada vez se ven más, por lo que la carga ecológica pasa a ser una parte primordial en el análisis de características deseables en un producto, que es de suma importancia avanzar en los conocimientos y métodos de análisis de esta naturaleza. Las herramientas como el EI99 rebasan el interés del sector empresarial, debiendo incorporarlas en los estudios y proyectos académicos para que las metodologías que las ocupen, encuentren información numérica precisa para diferentes materiales, procesos, y otras variables aquí mencionadas.

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# ANEXOS

1. Tablas contenidas en el manual del Eco-indicador 99

### Production of ferro metals (in millipoints per kg)

| | Indicator | Description | |
|---|---|---|---|
| Cast iron | 240 | Casting iron with > 2% carbon compound | 1 |
| Converter steel | 94 | Block material containing only primary steel | 1 |
| Electro steel | 24 | Block material containing only secondary scrap | 1 |
| Steel | 86 | Block material containing 80% primary iron, 20% scrap | 1 |
| Steel high alloy | 910 | Block material containing 71% primary iron, 16% Cr, 13% Ni | 1 |
| Steel low alloy | 110 | Block material containing 93% primary iron, 5% scrap, 1% alloy metals | 1 |

### Production of non ferro metals (in millipoints per kg)

| | Indicator | Description | |
|---|---|---|---|
| Aluminium 100% Rec. | 60 | Block containing only secondary material | 1 |
| Aluminium 0% Rec. | 780 | Block containing only primary material | 1 |
| Chromium | 970 | Block, containing only primary material | 1 |
| Copper | 1400 | Block, containing only primary material | 1 |
| Lead | 640 | Block, containing 50% secondary lead | 1 |
| Nickel enriched | 5200 | Block, containing only primary material | 1 |
| Palladium enriched | 4600000 | Block, containing only primary material | 1 |
| Platinum | 7000000 | Block, containing only primary material | 1 |
| Rhodium enriched | 12000000 | Block, containing only primary material | 1 |
| Zinc | 3200 | Block, containing only primary material (plating quality) | 1 |

### Processing of metals (in millipoints)

| | Indicator | Description | |
|---|---|---|---|
| Bending–aluminium | 0.000047 | one sheet of 1mm over width of 1 metre; bending 900 | 4 |
| Bending–steel | 0.00008 | one sheet of 1mm over width of 1 metre; bending 900 | 4 |
| Bending–RVS | 0.00011 | one sheet of 1mm over width of 1 metre; bending 900 | 4 |
| Brazing | 4000 | per kg brazing, including brazing material (45% silver, 27% copper, 25% tin) | 1 |
| Cold roll into sheet | 18 | per thickness reduction of 1 mm of 1 m2 plate | 4 |
| Electrolytic Chromium plating | 1100 | per m2, 1 _m thick, double sided; data fairly unreliable | 4 |
| Electrolytic galvanising | 130 | per m2, 2.5 _m thick, double sided; data fairly unreliable | 4 |
| Extrusion – aluminium | 72 | per kg | 4 |
| Milling, turning, drilling | 800 | per dm3 removed material, without production of lost material | 4 |
| Pressing | 23 | per kg deformed metal. Do not include non-deformed parts! | 4 |
| Spot welding–aluminium | 2.7 | per weld of 7 mm diameter, sheet thickness 2 mm | 4 |
| Shearing/stamping–aluminium | 0.000036 | per mm2 cutting surface | 4 |
| Shearing/stampin–steel | 0.00006 | per mm2 cutting surface | 4 |
| Shearing/stamping–RVS | 0.000086 | per mm2 cutting surface | 4 |
| Sheet production | 30 | per kg production of sheet out of block material | 4 |
| Band zinc coating | 4300 | (Sendzimir zink coating) per m2, 20-45 _m thick, including zinc | 1 |
| Hot galvanising | 3300 | per m2, 100 _m thick, including zinc | 1 |
| Zinc coating (conversion um) | 49 | per m2, 1 extra _m thickness, including zinc | 1 |

**Production of plastic granulate (in millipoints per kg)**

| | Indicator | Description | |
|---|---|---|---|
| ABS | 400 | | 3 |
| HDPE | 330 | | 1 |
| LDPE | 360 | | 1 |
| PA 6.6 | 630 | | 3 |
| PC | 510 | | 1 |
| PET | 380 | | 3 |
| PET bottle grade | 390 | used for bottles | 3 |
| PP | 330 | | 3 |
| PS (GPPS) | 370 | general purposes | 3 |
| PS (HIPS) | 360 | high impact | 1 |
| PS (EPS) | 360 | expandable | 3 |
| PUR energy absorbing | 490 | | 3 |
| PUR flexible block foam | 480 | for furniture, bedding, clothing | 3 |
| PUR hardfoam | 420 | used in white goods, insulation, construction material | 1 |
| PUR semi rigid foam | 480 | | 3 |
| PVC high impact | 280 | Without metal stabilizer (Pb or Ba) and without plasticizer (see under Chemicals) | 1 |
| PVC (rigid) | 270 | rigid PVC with 10% plasticizers (crude estimate) | 1* |
| PVC (flexible) | 240 | Flexible PVC with 50% plasticizers (crude estimate) | 1* |
| PVDC | 440 | for thin coatings | 3 |

**Processing of plastics (in millipoints)**

| | Indicator | Description | |
|---|---|---|---|
| Blow foil extrusion PE | 2.1 | per kg PE granulate, but without production of PE. Foil to be used for bags | 2 |
| Calandering PVC foil | 3.7 | per kg PVC granulate, but without production of PVC | 2 |
| Injection moulding – 1 | 21 | per kg PE, PP, PS, ABS, without production of material | 4 |
| Injection moulding – 2 | 44 | per kg PVC, PC, without production of material | 4 |
| Milling,turning,drilling | 6.4 | per dm3 machined material, without production of lost material | 4 |
| Pressure forming | 6.4 | per kg | 4 |
| React.Inj.Moulding-PUR | 12 | per kg, without production of PUR and possible other components | 4 |
| Ultrasonic welding | 0.098 | per m welded length | 4 |
| Vacuum-forming | 9.1 | per kg material, but without production of material | 4 |

**Production of rubbers (in millipoints per kg)**

| | Indicator | Description | |
|---|---|---|---|
| EPDM rubber | 360 | Vulcanised with 44% carbon, including moulding | 1 |

**Production of packaging materials (in millipoints per kg)**

| | Indicator | Description | |
|---|---|---|---|
| Packaging carton | 69 | $CO_2$ absorption in growth stage disregarded | 1 |
| Paper | 96 | Containing 65% waste paper, $CO_2$ absorption in growth stage disregarded | 1 |
| Glass (brown) | 50 | Packaging glass containing 61% recycled glass | 2 |
| Glass (green) | 51 | Packaging glass containing 99% recycled glass | 2 |
| Glass (white) | 58 | Packaging glass containing 55% recycled glass | 2 |

**Production of chemicals and others (in millipoints per kg)**

| | Indicator | Description | |
|---|---|---|---|
| Ammonia | 160 | $NH_3$ | 1 |
| Argon | 7.8 | Inert gas, used in light bulbs, welding of reactive metals like aluminium | 1 |
| Bentonite | 13 | Used in cat litter, porcelain etc. | 1 |
| Carbon black | 180 | Used for colouring and as filler | 1 |
| Chemicals inorganic | 53 | Average value for production of inorganic chemicals | 1 |
| Chemicals organic | 99 | Average value for production of organic chemicals | 1 |
| Chlorine | 38 | $Cl_2$. Produced with diaphragm production process (modern technology) | 1 |
| Dimethyl p-phthalate | 190 | Used as plasticizer for softening PVC | 1 |
| Ethylene oxide/glycol | 330 | Used as industrial solvent and cleaning agent | 1 |
| Fuel oil | 180 | Production of fuel only. Combustion excluded! | 1 |
| Fuel petrol unleaded | 210 | Production of fuel only. Combustion excluded! | 1 |
| Fuel diesel | 180 | Production of fuel only. Combustion excluded! | 1 |
| $H_2$ | 830 | Hydrogen gas. Used for reduction processes | 1 |
| $H_2SO_4$ | 22 | Sulphuric acid. Used for cleaning and staining | 1 |
| HCl | 39 | Hydrochloric acid, used for processing of metals and cleaning | 1 |
| HF | 140 | Fluoric acid | 1 |
| $N_2$ | 12 | Nitrogen gas. Used as an inert atmosphere | 1 |
| NaCl | 6.6 | Sodium chloride | 1 |
| NaOH | 38 | Caustic soda | 1 |
| Nitric acid | 55 | $HNO_3$. Used for staining metals | 1 |
| $O_2$ | 12 | Oxygen gas. | 1 |
| Phosphoric acid | 99 | $H_3PO_4$. Used in preparation of fertiliser | 1 |
| Propylene glycol | 200 | Used as an anti-freeze, and as solvent | 1 |
| R134a (coolant) | 150 | Production of R134a only! Emission of 1 kg R134a to air gives 7300 mPt | 1 |
| R22 (coolant) | 240 | Production of R22 only! Emission of 1 kg R22 to air gives 8400 mPt | 1 |
| Silicate (waterglass) | 60 | Used in the manufacture of silica gel, detergent manufacture and metal cleaning | 1 |
| Soda | 45 | $Na_2CO_3$. Used in detergents | 1 |
| Ureum | 130 | Used in fertilisers | 1 |
| Water decarbonized | 0.0026 | Processing only; effects on groundwater table (if any) disregarded | 1 |
| Water demineralized | 0.026 | Processing only; effects on groundwater table (if any) disregarded | 1 |
| Zeolite | 160 | Used for absorption processes and in detergents | 1 |

**Production of building material (in millipoints per kg)**

| | Indicator | Description | |
|---|---|---|---|
| Alkyd varnish | 520 | Production + emissions during use of varnish, containing 55% solvents | 5 |
| Cement | 20 | Portland cement | 1 |
| Ceramics | 28 | Bricks etc. | 1 |
| Concrete not reinforced | 3.8 | Concrete with a density of 2200 kg/m3 | 1 |
| Float glass coated | 51 | Used for windows, Tin, Silver and Nickel coating (77 g/m2) | 1 |
| Float glass uncoated | 49 | Used for windows | 1 |
| Gypsum | 9.9 | Selenite. Used as filler. | 1 |
| Gravel | 0.84 | Extraction and transport | 1 |
| Lime (burnt) | 28 | CaO. Used for production of cement and concrete. Can also be used as strong base | 1 |
| Lime (hydrated) | 21 | Ca(OH)2. Used for production of mortar | 1 |
| Mineral wool | 61 | Used for insulation | 1 |
| Massive building | 1500 | Rough estimate of a (concrete) building per m3 volume (capital goods) | 1 |
| Metal construction building | 4300 | Rough estimate of a building per m3 volume (capital goods) | 1 |
| Sand | 0.82 | Extraction and transport | 1 |
| Wood board | 39 | European wood (FSC criteria); CO2 absorption in growth stage disregarded | 1* |
| Wood massive | 6.6 | European wood (FSC criteria); CO2 absorption in growth stage disregarded | 1* |
| Land-use | 45 | Occupation as urban land per m2 yr | * |

**Heat (in millipoints per MJ)**

| | Indicator | Description | |
|---|---|---|---|
| | | Including fuel production | |
| Heat coal briquette (stove) | 4.6 | Combustion of coal in a 5-15 kW furnace | 1 |
| Heat coal (industrial furnace) | 4.2 | Combustion of coal in a industrial furnace (1-10MW) | 1 |
| Heat lignite briquet | 3.2 | Combustion of lignite in a 5-15kW furnace | 1 |
| Heat gas (boiler) | 5.4 | Combustion of gas in an atmospheric boiler (<100kW) with low NOx | 1 |
| Heat gas (industrial furnace) | 5.3 | Combustion of gas in an industrial furnace (>100kW) with low NOx | 1 |
| Heat oil (boiler) | 5.6 | Combustion of oil in a 10kW furnace | 1 |
| Heat oil (industrial furnace) | 11 | Combustion of oil in an industrial furnace | 1 |
| Heat wood | 1.6 | Combustion of wood; CO2 absorption and emission disregarded | 1* |

**Solar energy (in millipoints per kWh)**

| | Indicator | Description | |
|---|---|---|---|
| Electricity facade m-Si | 9.7 | Small installation (3kWp) with monocrystaline cells, used on building facade | 1 |
| Electricity facade p-Si | 14 | Small installation (3kWp) with polycrystaline cells, used on building facade | 1 |
| Electricity roof m-Si | 7.2 | Small installation (3kWp) with monocrystaline cells, used on building roof | 1 |
| Electricity roof p-Si | 10 | Small installation (3kWp) with polycrystaline cells, used on building roof | 1 |

**Electricity (in millipoints per kWh)**

| | Indicator | Description | |
|---|---|---|---|
| | | Including fuel production | |
| Electr. HV Europe (UCPTE) | 22 | High voltage (> 24 kVolt) | 1 |
| Electr. MV Europe (UCPTE) | 22 | Medium voltage (1 kV – 24 kVolt) | 1 |
| Electr. LV Europe (UCPTE) | 26 | Low voltage (< 1000Volt) | 1 |
| Electricity LV Austria | 18 | Low voltage (< 1000Volt) | 1 |
| Electricity LV Belgium | 22 | Low voltage (< 1000Volt) | 1 |
| Electricity LV Switzerland | 8.4 | Low voltage (< 1000Volt) | 1 |
| Electricity LV Great Britain | 33 | Low voltage (< 1000Volt) | 1 |
| Electricity LV France | 8.9 | Low voltage (< 1000Volt) | 1 |
| Electricity LV Greece | 61 | Low voltage (< 1000Volt) | 1 |
| Electricity LV Italy | 47 | Low voltage (< 1000Volt) | 1 |
| Electricity LV the Netherlands | 37 | Low voltage (< 1000Volt) | 1 |
| Electricity LV Portugal | 46 | Low voltage (< 1000Volt) | 1 |

**Transport (in millipoints per tkm)**

| | Indicator | Description | |
|---|---|---|---|
| | | Including fuel production | |
| Delivery van <3.5t | 140 | Road transport with 30% load, 33% petrol unleaded, 38% petrol leaded, 29% diesel (38% without catalyst) (European average including return) | 1 |
| Truck 16t | 34 | Road transport with 40% load (European average including return) | 1 |
| Truck 28t | 22 | Road transport with 40% load (European average including return) | 1 |
| Truck 28t (volume) | 8 | Road transport per m3km. Use when volume in stead of load is limiting factor | 1* |
| Truck 40t | 15 | Road transport with 50% load (European average including return) | 1 |
| Passenger car W-Europe | 29 | Road transport per km | 1 |
| Rail transport | 3.9 | Rail transport, 20% diesel and 80% electric trains | 1 |
| Tanker inland | 5 | Water transport with 65% load (European average including return) | 1 |
| Tanker oceanic | 0.8 | Water transport with 54% load (European average including return) | 1 |
| Freighter inland | 5.1 | Water transport with 70% load (European average including return) | 1 |
| Freighter oceanic | 1.1 | Water transport with 70% load (European average including return) | 1 |
| Average air transport | 78 | Air transport with 78% load (Average of all flights) | 6 |
| Continental air transport | 120 | Air transport in a Boeing 737 with 62% load (Average of all flights) | 6 |
| Intercontinental air transport | 80 | Air transport in a Boeing 747 with 78% load (Average of all flights) | 6 |
| Intercontinental air transport | 72 | Air transport in a Boeing 767 or MD 11 with 71% load (Average of all flights) | 6 |

**Recycling of waste (in millipoints per kg)**

| | Indicator | | | Description | |
|---|---|---|---|---|---|
| | Total | Process | Avoided product | Environmental load of the recycling process and the avoided product differs from case to case. The values are an example for recycling of primary material. | |
| Recycling PE | -240 | 86 | -330 | if not mixed with other plastics | 7* |
| Recycling PP | -210 | 86 | -300 | if not mixed with other plastics | 7* |
| Recycling PS | -240 | 86 | -330 | if not mixed with other plastics | 7* |
| Recycling PVC | -170 | 86 | -250 | if not mixed with other plastics | 7* |
| Recycling Paper | -1,2 | 32 | -33 | Recycling avoids virgin paper production | 2* |
| Recycling Cardboard | -8,3 | 41 | -50 | Recycling avoids virgin cardboard production | 2* |
| Recycling Glass | -15 | 51 | -66 | Recycling avoids virgin glass production | 2* |
| Recycling Aluminium | -720 | 60 | -780 | Recycling avoids primary aluminium. | 1* |
| Recycling Ferro metals | -70 | 24 | -94 | Recycling avoids primary steel production | 1* |

**Waste treatment (in millipoints per kg)**

| | Indicator | Description | |
|---|---|---|---|
| **Incineration** | | Incineration in a waste incineration plant in Europe. Average scenario for energy recovery. 22% of municipal waste in Europe is incinerated | |
| Incineration PE | -19 | Indicator can be used for both HDPE and LDPE | 2* |
| Incineration PP | -13 | | 2* |
| Incineration PUR | 2,8 | Indicator can be used for all types of PUR | 2* |
| Incineration PET | -6,3 | | 2* |
| Incineration PS | -5,3 | Relatively low energy yield, can also be used for ABS, HIPS, GPPS, EPS | 2* |
| Incineration Nylon | 1,1 | Relatively low energy yield | 2* |
| Incineration PVC | 37 | Relatively low energy yield | 2* |
| Incineration PVDC | 66 | Relatively low energy yield | 2* |
| Incineration Paper | -12 | High energy yield $CO_2$ emission disregarded | 2* |
| Incineration Cardboard | -12 | High energy yield $CO_2$ emission disregarded | 2* |
| Incineration Steel | -32 | 40% magnetic separation for recycling, avoiding crude iron (European average) | 2* |
| Incineration Aluminium | -110 | 15% magnetic separation for recycling, avoiding primary aluminium | 2* |
| Incineration Glass | 5,1 | Almost inert material, indicator can be used for other inert materials | 2 |
| | | | |
| **Landfill** | | Controlled landfill site. 78% of municipal waste in Europe is landfilled | |
| Landfill PE | 3,9 | | 2 |
| Landfill PP | 3,5 | | 2 |
| Landfill PET | 3,1 | | 2 |
| Landfill PS | 4,1 | Indicator can also be used for landfill of ABS | 2 |
| Landfill EPS foam | 7,4 | PS foam, 40 kg/m3, large volume | 2* |
| Landfill foam 20kg/m3 | 9,7 | Landfill of foam like PUR with 20kg/m3 | 2* |
| Landfill foam 100kg/m3 | 4,3 | Landfill of foam like PUR with 100kg/m3 | 2* |
| Landfill Nylon | 3,6 | | 2* |
| Landfill PVC | 2,8 | Excluding leaching of metal stabilizer | 2 |

| | | | |
|---|---|---|---|
| Landfill PVDC | 2,2 | | 2 |
| Landfill Paper | 4,3 | $CO_2$ and methane emission disregarded | 2 |
| Landfill Cardboard | 4,2 | $CO_2$ and methane emission disregarded | 2 |
| Landfill Glass | 1,4 | Almost inert material, indicator can also be used for other inert materials | 2 |
| Landfill Steel | 1,4 | Almost inert material on landfill, indicator can be used for ferro metals | 2 |
| Landfill Aluminium | 1,4 | Almost inert material on landfill, indicator is valid for primary and recycled alu. | 2 |
| Landfill of 1 m3 volume | 140 | Landfill of volume per m3, use for voluminous waste, like foam and products | * |
| **Municipal waste** | | In Europe, 22% of municipal waste is incinerated, 78% is landfilled. | |
| | | Indicator is not valid for voluminous waste and secondary materials | |
| Municipal waste PE | -1,1 | | 2* |
| Municipal waste PP | -0,13 | | 2* |
| Municipal waste PET | 1 | | 2* |
| Municipal waste PS | 2 | Not valid for foam products | 2* |
| Municipal waste Nylon | 3,1 | | 2* |
| Municipal waste PVC | 10 | | 2* |
| Municipal waste PVDC | 16 | | 2* |
| Municipal waste Paper | 0,71 | | 2* |
| Municipal waste Cardboard | 0,64 | | 2* |
| Municipal waste ECCS steel | -5,9 | Valid for primary steel only! | 2* |
| Municipal waste Aluminium | -23 | Valid for primary aluminium only! | 2* |
| Municipal waste Glass | 2,2 | | 2* |
| **Household waste** | | Separation by consumers of waste for recycling (average European scenario) | |
| Paper | -0,13 | 44% separation by consumers | 2* |
| Cardboard | -3,3 | 44% separation by consumers | 2* |
| Glass | -6,9 | 52% separation by consumers | 2* |

2. Artículo: Selección de materiales y diseño para el desarrollo de productos sustentables. Publicado por Lennrt Y. Ljunberg.

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# Materials selection and design for development of sustainable products

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**Abstract**

How can we develop and produce more sustainable products? The author reviews current methods as well as presents models on how to develop sustainable products. Different methods for achieving products with as low environmental impact as possible are shown as well as principles for product development with special regards to materials selection, design, the product in use and recycling are given.

Definition of a sustainable product, triple bottom line, dematerialisation, recycling, design considerations, ISO 14001 standard and the EMAS (Eco Management and Audit Scheme) regulation are examples of areas, which are reviewed in this article. Life cycle assessment, environmental impact, eco-efficiency, environmental space, market contacts, cultural aspects, fashion and trends are also reviewed.

Guidelines for sustainable product development are presented with special regard to material, design and ecology. A description of materials selection and models for design based on a sustainable society is also presented.


*Keywords:* Sustainable product development; Design; Recycling; Materials selection; Environmental impact; Ecology

## 1. Background

In a world with limited resources and serious environmental impacts, it is obvious that a more sustainable life style will be more and more important. Material products, like paperclips, telephones or cars, are examples of products, which can consist of one single or up to many thousands of different materials. Estimations tell us that we have to deal with probably over 100.000 commercial materials on the market with respect to the great amount of variants. Extraction, refinement, transports, product use phase, recycling or deposition are examples of complex areas, which can give different types of impacts on the environment.

During the last century, environmental problems were often seen as local problems due to the impact from a certain product. However, today it becomes more obvious that the problems are much more complex and related to all the phases in a product's life cycle from extraction of material to waste or deposition of the used product [1].

The fact that even in the Bible man was seen as having dominion over the living things and subdues the earth (Genesis 1:28) has been neglected in various areas in the world. Rapid technical developments, during the last centuries, have for example caused serious environmental impact, which can be regarded as an un-sustainable life style. Unsustainability is mainly caused by the current global situation.

There are today at least four basic problems, which are more or less unsolved:

- Over-consumption.
- Resource utilisation.
- Pollution.
- Over-population.

*Over-consumption*. The use of material today for energy, packaging and the products themselves has increased at least 20-fold per capita in many highly industrialised countries from the end of the 19th century until today [2,3]. More components and more mixed materials in various products, which demand transportation, in combination with generally higher energy consumption around the

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world, are only examples of over-consumption. The nature cannot sustain today's growth rate of up to about 5% in some countries, without serious impact in the long run [4].

*Resource utilisation*. The human productivity has not been able to co-operate with the nature regarding sustainability. Only a few percent of the material and energy theoretically required for producing products today is used for the product itself. A lot of energy and material is for example lost during production and transportation, which includes waste material and emissions, especially for non-recycled products [2].

*Pollution*. Even if all companies reach zero emissions right now, the earth would still be seriously affected by the emissions so far [5].

*Over-population*. The world could have more than ten billions inhabitants by 2025. It is clear as to how this situation will lead to less sustainability with more and more environmental impact. Even if many products like, e.g., cars, have become more environmental friendly over the last decades, they cannot obviously reduce the total amount of materials and energy used due to the population increase.

However, there are no possibilities to reduce all environmental impacts to zero. The increase of the entropy on the earth is a fact, which has been proven by thermodynamic laws. It is clear that the earth is populated by its inhabitants and this causes a situation which is "non-sustainable by itself".

## 2. Sustainable product development

There is no simple way of how to develop 'sustainable products'. The complexity of the situation has already been presented above and according to the thermodynamic laws, total sustainable products are not possible to develop in general. However, there are many different approaches and definitions of how to develop sustainable products, which will be studied and analysed in this article. The main problem is still unsolved which is the fact that the world is not sustainable by itself. Life on the earth cannot go on forever in a way that the nature can be brought back to some sort of an initial condition without drastic influences from systems outside the earth causing a reduction of the entropy in our earthly system. Most definitions of sustainable products among researchers in this area have shown the lack of understanding the fact that our planet is not a sustainable system by itself! However, the following definition will be applied in this paper:

### 2.1. Example of a simple definition of a sustainable product

- A sustainable product is a product, which will give as little impact on the environment as possible during its life cycle.

The life cycle in this simple definition includes extraction of raw material, production, use and final recycling (or deposition). The material in the product as well as the material (or element) used for producing energy is also included here. This definition is in fact not totally defined according to the amount of impact on the environment or the nature. Hence the impact cannot be zero, it must be 'reasonably minimised'. This opens up the fact that there will be similar products, which are more or less 'sustainable' when they are compared side by side!

As can be understood from above, there are many different aspects and details related to this definition. This paper will elucidate the product development of sustainable products by presenting some important aspects and then discuss ways to measure the 'sustainability'.

### 2.2. A sustainable product must be a successful product

A good sustainable product must give as much satisfaction as possible for the user. If not, it will be unsuccessful on the market and an economic failure. There are estimations, which tell us that nearly 90% of all technically good products will not be a success on the market for various reasons [6]. When releasing sustainable products on the market, it is reasonable to believe that the risk for failure is not less. It is also important to inform people as to what basis a certain product is considered to be sustainable or not and why they should buy it.

### 2.3. Environmental marking or labelling of products

To inform customers whether a certain product is environmentally friendly, different kinds of environmental marking systems have been developed. Examples of these are the *EU sign* (a flower with 12 stars), the *Energy Star* (Emidast) Environmental Protection Agency in the USA, the *TCO sign* (Tjänstemännens Centralorganisation) in Sweden, *Svanen* (Standardiseringskommisionen i Sverige), *Umweltzeichen* (in Germany) or *Environmental choice* (in Australia). These kinds of markings are voluntary for the companies and can be used when a product fulfils certain requirements from the specific organisation [7]. However, the demands for producing environmentally friendly products are not clear and easy to understand for a general customer. Even for an expert it is problematic or impossible to determine which product of many similar ones is the best choice.

Other examples of marking are the *Panda* (WWF, World Wildlife Foundation) and the recycling mark with "three arrows". The Panda mark only tells us that money has been donated to WWF and the three arrows only indicate that the producing company is working with recyclable products.

### 2.4. Sustainable development

The following areas are examples of important issues connected to sustainable development [8]:

- *Environment*. The eco-system in the world must be treated in order to protect plants and animals. The environment must be seen as a part of the development process and not be taken for free to use.
- *Equity*. The issue of poverty and equal distribution and use of natural sources must be solved in order to maintain stable societies and equal value of people.
- *Futurity*. The impact from development must be seen in a long perspective in order to minimise the impact for future generations.

Another, rather new approach to meet the demand for measuring the sustainability of a product is to use the conception *Triple Bottom Line* (TBL). The TBL term was first coined by John Elkington and according to him: "…the term triple bottom line is used as a framework for measuring and reporting corporate performance against economic, social and environmental parameters". The TBL concept involves the traditional economic bottom line together with the society and the environment. This triad can simply be drawn as a triangle with the following corners: [9].

- Ecology (environmental protection).
- Equity (social equity).
- Economy (economic growth).

When developing a new product, it is illustrative to move between the three corners Ecology, Equity and Economy in order to obtain a suitable balance so that each category can be fulfilled in the best way. The ecological side emphasises, e.g., clean landscapes, pure air and water, while the equity side, e.g., can tell us if a certain product can lead to social welfare regardless of people's background and if it promotes fair compensation as well as health, safety, etc. The economy side tells us if it is possible to make profit on a product.

Another example of sustainable product development, which is based on TBL, but more product orientated, is the SPSD (Sustainable Product and Service Development). The SPSD method is designed to give more practical guidance to the industry and can be simplified with four stages: (1) Question the functionality already at the concept stage. (2) Determine all the life cycle stages. (3) Determine all supply chain companies. (4) Optimise the sustainability impacts. The criteria for optimising the sustainability in products and services are mainly: functionality, environmental impacts, social impacts, economic impacts, market demand, quality, customer requirements, technical feasibility, compliance with legislation and different specifications [10].

### 2.5. Environmental management systems, EMS, EMAS and ISO 14001

Earlier sustainable production with environmental issues was often seen as a problem for most companies. Today many companies can see the benefits of environmental production. Good reputation and even better economy by using recycled material, etc. in the production are examples of advantages. During the last decades, we have also seen that many companies have found that pollution prevention has become economically beneficial [5,11].

A way to create a systematic environmental plan for a producing company is to use international standardised Environmental Management Systems (EMSs). This has become more and more important for different companies all over the world [12].

EMSs can normally be described as a voluntary system. It can be seen as a tool for management that can be used to steer and control environmental efforts by computer controlling or performed by a special organisation. Any company that has taken steps towards environmental issues has in fact implemented an EMS [13]. EMS can simply be defined as "the part of the overall management system that includes the organisational structure, planning activities, responsibilities, practices, procedures, processes and resources for developing, achieving, reviewing and maintaining the environmental policy" [14].

In the early 1990s, the World Business Council for Sustainable Development (WBCSD) issued a declaration about the connection between environmental protection, economic growth and satisfaction of human needs [15]. The declaration led to the development of an international standard ISO 14001, which was released in 1996 by the International Standardisation for Organisation (ISO) in Switzerland [16,7]. ISO 14000 consists of a whole series of environmental standards based on the 14001 standard [17]. In 1993, the European Commission issued a regulation, called the Eco Management and Audit Scheme (EMAS) [18]. The EMAS regulation is intended to act mainly as a document to provide a sustainable way of production in the European Union and it is a way to express the political request for the European Union. EMAS has also become an integrated part of laws regarding the environmental influence in the European Union. Both EMAS and ISO 14000 contain requirements for the EMS.

### 2.6. Environmental impact with the LCA-method

Life Cycle Assessment (LCA) is a useful tool for understanding the impact of the environment [19–22]. A product is evaluated step by step from cradle to grave, where cost, impact, expected lifetime, etc. can be evaluated in a quite easy way.

A simple way to account for an environmentally friendly production is to give every product an environmental load. This can be done with, for example, the Environmental Load Unit (ELU) index/kg or unit. ELU is a sum of the environmental load for a product with respect to production, material, transports, etc. during the whole lifetime of a certain product. The ELU can be seen as a way to express how much it will cost to restore the environment as it used to be before a certain impact.

However, note that there is no way that is 100% accurate when comparing different production, breaking down or recycling methods. It is for example not easy to compare glass bottles or paper packs, e.g., milk, and to say what is the most environmentally friendly (or sustainable) material for milk transportation. The paper pack is used only once and then normally burnt. The glass bottle is used a number of times but needs extra energy for transportation (because of its quite high weight) and needs detergents and water for cleaning before every new filling. The transportation to different customers and the environmental influence from the cleaning process must then be weighted and estimated. The emissions from burning or recycling of the paper must be compared with, e.g., the discharge from the detergents. Today we have a certain way of weighing the emission factors affecting the environment, but tomorrow it can be changed, because of increased knowledge of certain risks of a special emission.

The LCA methodology is probably the most widespread technique for evaluating environmental impacts associated with material products [23]. There are typically six important steps involved in an LCA evaluation [24]:

1. Extract from material.
2. Manufacturing with, e.g., ennobling and refinement.
3. Packaging stage.
4. Transportation of, e.g., material and the ready product.
5. Product user stage.
6. Product disposal stage.

These steps can then be divided into smaller steps in order to get a more precise view of the life cycle, like: Extract of material, Design, Market research and Product Development, Process planning, Purchase of materials, Production and Assembly, Product Control, Treatment of waste, emissions and noise, Packaging and storage, Marketing, Selling or Leasing, Delivery, Use, Service and Maintenance, Renovation/Upgrading, Reuse/Recycling and Final utilisation.

Some important methods for evaluating environmental impacts together with the LCA method are: Eco-Indicator '99 [25], Environmental Priority System (EPS) [26] and Tellus [27]. The evaluation makes it easier to compare different materials, manufacturing methods, service intensity, etc. side by side, which is of vital importance when developing sustainable products [28,29].

### 2.7. Eco-efficiency and eco-design

Eco-efficiency is a way of running a business in a more effective way in both ecological conditions [30]. However, the conception does not take into account the environmental impact after the product has been sold. The LCA is here a more comprehensive way of determining the total environmental impact. Eco-Design is also known as Design for Environment. The strategies for Eco-Design are, e.g., to use materials with low environmental impact, choosing clean production processes, avoiding hazardous and toxic materials, maximising the efficiency of the energy used for production and for the product in use and designing for waste management and recycling.

### 2.8. Environmental space

In order to achieve a sustainable development, the concept of Environmental Space has been developed [31]. The concept is a way to get a more equal distribution of the usage of the environment and the quantity of natural resources per capita. The concept is focusing on reduced use of resources in product development focused on, e.g., recycling, prolonged product lifetime, easy repairability as well as minimising materials, toxic emissions and consumption. Ecological design, reduced use of energy, and focus on utility instead of ownership are also important issues in this concept [32].

### 2.9. Market contacts and product phases in the market

Good market contacts, i.e., close contacts with customers, are essential for releasing products in the market. If a "sustainable product" is expected to be of minor interest for the market, do not release it. A failure can result in bad reputation for the releasing company and for sustainable products in general. Try to wait until the market is ready for a certain sustainable product or create a need for the product with for example advertising, logical arguments or combine the sustainability with another feature, which is attractive for the market [33,6].

Most products have a limited life on the market. A typical product can be classified into four different phases on the market: introduction, growth, maturity and decline [34]. A certain product should normally not be released on the market during the maturity or decline phase. An exception is when the product has something trend braking which can lead to a new growth at an earlier products expense. A sustainable image could be such a trend breaker.

### 2.10. Legislation and safety precautions

Manufacturing and release of products are also restricted with different laws, which can differ from country to country [35,7]. Introduction of a new environmentally friendly technique or material can lead to successors and even be a reason to forbid older techniques. For example, when catalytic converters for petrol emissions from cars came, it was a reason to forbid the production of traditional carburettor cars, in many countries. A new material, which looks very good in the beginning, can almost over a night become dangerous when certain problems are verified. This was the fact for asbestos, which is now forbidden to be used in many countries because of the detection of its risk for causing lung cancer.

A product itself must also be safe to use. Safety is in many cases determined by different laws. However, many trend braking safety equipments like safety belts for cars and earth fault breakers in electric equipments are examples of inventions, which can give an extended lifetime for a product. Such safety arrangements can consequently lead to more sustainable products.

### *2.11. Cultural aspects*

In order to develop sustainable products, it is of importance to know the cultural aspects. In Scandinavian countries wood is popular as a building material for outer walls, because it is cheap there and makes the houses easy to insulate, which is important during the cold winter seasons. In many other countries, wood is a material, which has a reputation to be inferior to stone or brick. This is sometimes true, but has also to do with the traditions among people, i.e., what people think and what they feel about a certain material. Wooden floors are, in many countries, popular because of their surface characteristics and softness, but in spite of the fact that a concrete floor is more sustainable and durable. The physical aspects, like hardness, lifetime, etc. are important for many people, while for others, the metaphysical aspects (feelings) are dominating when choosing a wooden floor [36,37]. Stainless steel or laminated wood is quite typical for kitchen benches in northern countries, while stone is dominating in the Mediterranean countries. This is another example of a cultural aspect and tradition.

### *2.12. Fashion and trends*

Which kind of design, material, colour, etc. will be in fashion tomorrow? A sustainable product must be in fashion to be popular on the market. Fashion trends are not easy to predict, but very important to anticipate. Close market contacts are important here, but trend braking ideas can also direct the market into new trends [6].

A somewhat problematic trend today is the *Throwaway Society*. The mentality of "use, wear and throw away" must generally be regarded as a non-sustainable way of living. For example, most of the mobile phones used among younger people today seem to be replaced by newer ones after only three years of use. DVD-players, watches, clothes, etc. are used and changed more and more often because of the trend, which tells us to have only modern things, which are in fashion. An example of tackling this problem is to exchange ideas between designers, engineers, socialists, scientists and marketing specialists. A team from Sheffield Hallam University, with funding from Engineering and Physical Sciences Research Council (EPSRC), has focused on how products like furniture, cars, clothes, household appliances and other consumer products can be more sustainable [38]. This is an interesting example of cooperation between people from the academic as well as the industrial field.

### *2.13. Guidelines for sustainable development*

In order to develop more sustainable products, some important points are to be noticed [20,39–41]:

- Reduce the materials and the use of energy for a product including services during its lifetime.
- Reduce emissions, dispersion and creation of toxics during its lifetime.
- Increase the amount of recyclable materials.
- Maximise the sustainable use of renewable resources.
- Minimise the service intensity for products and services.
- Extend the useful life for a product.
- Assess and minimise the environmental impact over the product lifetime.
- Having a "Functional economy" is a way to substitute products with services.
- Use "Reverse logistics" which means that all efforts are used in order to reuse products and materials.
- Increase the efficiency of a product in the usage phase.

## 3. Guidelines for materials selection and design

### *3.1. Materials overview*

A technical product is usually made of one or several materials. However, there are examples of immaterial products like computer programs. The sustainability of a certain material based product is mainly depending on the material or materials used for the product itself or during its lifetime according to, e.g., a LCA (Life Cycle Assessment). During the life cycle of a material product, different stages are passed, like material extraction, manufacturing, packing, transportation, product use and disposal. All these stages will give a certain environmental impact, which is mainly caused by the materials involved in the different stages [24]. Hence, the selection of materials for a certain product is of vital importance, while the material determines the use of our natural resources as well as the amount of energy used for the production and the use of the product [42–44]. Manufacturing of products typically involves chemical substances like cutting fluids during machining, cleaning aids, paint, etc. Technical lifetime, maintenance, service and repair of a product are other examples of areas, which are typically dependent on the material used for the product itself.

The use of renewable materials, like wood versus non-renewable materials, like plastics (made of raw oil), is also important to consider in product development. Renewable materials are materials which in a short time can be formed again in the nature and give no or very little impact on the environment. If, e.g., a tree is cut, used in a product and burnt and a new tree is planted, the new growing tree can bind the carbon dioxide formed when the old tree is burnt. If the ash, containing minerals and fertilizers, is brought back to the earth, the new tree will use the ash when growing. This is an example of the life cycle of a renewable material. However, if a forest has been cut down and no new trees have been planted again, the environmental balance is changed. This can lead to earth destruction, a change in the climate due to changed water balance and in the worst case the forming of a desert. When a tree is cut a price can be estimated to ensure the sustainability, which in this case means that a new tree is planted and the forests are kept and maintained in the future. A polymer made from raw oil is an example of a non-renewable material, while the raw oil cannot easily be brought back to its initial state again. This leads to an environmental impact when raw oil is used. The term renewable is typically used for organic materials.

Selection of material is traditionally made by technical demands like price, strength of material, temperature stability, density, hardness, etc. [45,46]. However, for a successful product development the technical or physical demands are not enough. Factors like reputation, fashion, product, cultural aspects, etc. must also be taken into account when developing sustainable products. As a result of metaphysical reasons like 'feelings' for a certain material, the materials selection is often not easy [36]. Clothes made of synthetic fibres are often more easy to clean and to keep free from wrinkles, but the natural materials are generally more popular because of its feeling and the fact that they are generally more popular. Wooden floors are more popular for certain people even if concrete floors are more wear resistant and durable. Anyhow, materials selection for sustainable products is mainly based on the ultimate impact on the nature as well as market demands and economic factors.

As mentioned earlier, estimations tell us that there are more than 100.000 different kinds of commercial materials on the market if we include all the variants in materials composition, blending, heat treatment, etc. The fact that not only objective methods for selection of materials, but also subjective have to be regarded does not make the selection easier. The following division of materials in groups is a way to simplify the selection as well as give an overview over the properties and the sustainability.

Structural materials for material products can be divided into six groups: *Metals*, *ceramics*, *synthetic polymers*, *natural organic materials, natural inorganic materials and composites*. These groups cover probably more than 99% of all materials used in mechanical, civil and electrical engineering. Exceptions are chemical substances like fluids and gases, which will not be covered here. See Table 1 below!

Comments to Table 1:

- *Metals* are typically cheap and easy to recycle into new products by re-melting. A disadvantage is the typical high weight (density) for many metals like steel and copper alloys, which may lead to energy consuming transportations, as well as the amount of energy required for re-melting due to typical high melting points for metals in general. The corrosion resistance for especially steel is also low. Corrosion protection often needs more or less toxic chemical treatments or paints. Aluminium and its alloys are on the other hand a common example of a quite corrosion resistant metal, which is also light, strong and easy to recycle due to a low melting point (about 600 °C). The sustainability gives generally the marks 2–3 depending on, e.g., melting temperature (high melting temperatures lead to high energy consumption for melting) and toxicity from the material itself or from extraction processes. Toxic metals even in thin layers or in alloys typically give the mark 1.
- *Ceramics* are typically light and non-toxic. The raw material is generally clay for traditional ceramics and pure oxides, nitrides or carbides for advanced ceramics. They are often not only very durable, hard, high temperature and corrosion resistant, but also brittle. Ceramics are seldom recycled into new products because of the need of crushing, grinding and re-burning, which is typically more costly and energy requiring than producing products from new raw material. The used products can for example be crushed and used as fillers in building technique. The sustainability mark is typically 3 for materials based on natural clays and 2 for materials containing toxic components or some advanced ceramics like fibres, which might give higher environmental impact due to the manufacturing process.
- *Synthetic polymers* or Plastics and rubber are generally made of raw oil. Anyhow, many polymers can be made from natural organic materials like wood. If raw oil based polymers are recycled by burning the material is not renewable, because the amount of oil is limited and new oil will not be formed in a short time. Many polymers like polyethylene (PE) can easily be burnt individually or together with for example paper during formation of carbon dioxide and water. Carbon dioxide is harmless in smaller amounts, but is regarded to increase the environmental impact due to the greenhouse effect in the atmosphere. Some polymers, especially those containing halogens, like Teflon® (PTFE) and polyvinyl chloride (PVC) are quite harmful to burn due to the harmful fumes. Re-melting is here recommended. Due to low re-melting temperatures for many thermoplastic polymers (typically about 200 °C) compared with those for most metals, the energy consumption is quite low. Controlled burning with exhaust cleaning is another possibility for recycling. A problem when recycling plastics is to determine which kind of polymer a product is made of. However, international labelling of polymers has minimised this problem during the last decades [42]. Thermosetting plastics and rubber are examples of polymers, which cannot be re-melted which means that deposition or use as filler material or chemical dissociation is recommended for recycling. The sustainability marks vary from 1 for

Table 1
The six typical product material groups, as well as examples and aspects for developing sustainable products are presented

| Material group | Examples on materials | Typical Advantages | Typical disadvantages | Classification of the sustainability[a] |
|---|---|---|---|---|
| Metals | • Steel ($Fe + C$)<br>• Aluminium<br>• Bronze (e.g., $Cu + Sn$) | • Durable and strong<br>• Often plastic formable<br>• Often cheap | • High cost for machining<br>• Mostly corrosion sensitive | • Easy recyclable (re-meltable)<br>2–3 |
| Ceramics | Synthetic materials like:<br>• Porcelain (clay)<br>• Mineral glass<br>• $Al_2O_3$, $Si_3N_4$, SiC, etc. | • Non toxic<br>• Light<br>• Hard and durable<br>• Corrosion resistant<br>• High temp. resistant | • Brittle<br>• High cost for machining when burnt<br>• Not suitable for load in tension | • Easy to deposit (non toxic)<br>• Possible but expensive to re-melt<br>2–3 |
| Synthetic polymers | • Thermoplastics (e.g., PE, PS, PC, PP)<br>• Two component polymers (e.g., epoxy)<br>• Rubber (e.g., Isopren) | • Non toxic<br>• Light<br>• Cheap and easy forming<br>• Often easy to recycle (e.g., by re-melting or burning) | • Sometimes very toxic when burnt<br>• Sensitive to high temperatures | • Typically non-renewable<br>• Often easy to re-melt or burn<br>1–3 |
| Natural organic materials | • Wood<br>• Cotton<br>• Silk | • Renewable<br>• Light<br>• Cheap and easy forming<br>• Recyclable by, e.g., burning | • Decomposes easily<br>• Not durable<br>• Toxic when impregnated | • Recyclable by, e.g., burning<br>• Renewable<br>2–3 |
| Natural inorganic materials | • Stone<br>• Minerals | See ceramics above! | • Brittle<br>• High cost for machining<br>• Not suitable for load in tension | See ceramics above!<br>3 |
| Composites | • Mixed materials, e.g.: PS + glassfibres, Cu + W-fibres, Rubber + textilfibres, asphalt (oil + stone), Wood Polymer Composites (WPC) | • Optimised use of the materials<br>• Often very strong and light | • Often expensive to produce<br>• Very various properties for various composites | • Typically low sustainability due to separation problems for the mixed materials<br>1–2 |

Note that the advantages/disadvantages and the 'sustainability' can change due to the specific material type and the examples are not valid for all materials in a certain material group.
[a] The sustainability is estimated from a scale 1 to 3, where 3 indicates the highest (or best) sustainability and 1 the lowest.

toxic (e.g., halogen containing polymers) and non-renewable materials, to 3 for polymers based on natural organic raw material.

- *Natural organic materials* like wood and cotton are always popular materials in various forms. Recycling can easily be done in the form of energy recycling in, e.g., thermal power plants for heating. Carbon dioxide and water are formed and carbon dioxide is here bonded directly from the air by new growing plants and trees. The carbon dioxide content in the atmosphere will therefore not increase when natural organic materials are burnt. Hence, these materials are typically renewable. However, colouring and impregnation to avoid breaking-down can be quite toxic [47]. Such toxicants can give serious environmental impact after energy recycling or putrefaction. The sustainability mark is typically 3 but for impregnated material the mark can go down to 2 (or even 1).
- *Natural inorganic materials* like stone, rock or various minerals are quite similar to the synthetic made ceramics. Therefore, the typical sustainability mark will be 3 if no toxic or radioactive elements are involved.
- *Composites* have become more and more popular during the last years especially in the form of ceramic fibres mixed in a plastic resin. If these materials can be burnt as a recycling method where no toxicants are formed, the sustainability can be even 3 if the materials are renewable. However, composites in general are not renewable and the problems to separate the different materials used in composites make these materials generally quite unsustainable, which gives the marks 1 or 2 for the sustainability.

According to Table 1 and the comments above, natural materials, polymers based on renewable raw materials, as well as ceramics and some metals seem to be sustainable materials for the future. However, excessive use of wood and cotton may lead to very serious environmental impact due to utilisation of forests and hence earth degradation, water problems, etc. This means that a material itself can be sustainable for the product during use and recycling, while the material extraction can lead to serious impacts. Polymers based on raw oil should be used carefully especially if it is not possible to recycle by re-melting. Composites must be used restrictively with regards especially to the materials, which builds up the composite. It is also important to consider the possibilities of how to separate the specific materials.

### 3.2. Recycling

The last steps in an LCA process deal with recycling and final utilisation of the material in a product. However, in the early stages of product development, recycling or deposition must be taken into account to achieve sustainable products with a minimum of environmental impact. The materials selection today must strongly be directed to the future recycle-ability of a product in order to meet the demands of the future. Recycling can be done in different ways like:

- *Energy recycling*. The material is here burnt and the energy is used for heating.
- *Material recycling*. The material is typically re-melt or reshaped in order to make new products.
- *Re-use (or recycling)*. The product or parts of it can be used again, sometimes after reconditioning. Reconditioned products or spare parts are sold at a lower price than a new part which is typical for second hand markets (used car parts, etc.).
- *Breakdown*. Natural organic materials, many synthetic polymers and some metals can be broken down naturally in the nature or by chemical methods to environmentally friendly products or chemicals. These materials are often referred to as degradable or biodegradable materials [48]. Typical processes are corrosion, composting and putrefaction.

When recycling is not possible or suitable, deposition can be an alternative:

- *Deposition.* Deposition can be an alternative if a product is not suitable for the processes mentioned above. This is a way to store materials during circumstances where as low environmental impact as possible for all time will be guaranteed. If the material is radioactive or toxic, it can be deposited in certain restricted areas or deep underground. Deposition is typically restricted by environmental legislation.

All processes mentioned above are generally restricted by environmental legislation, which is a way to minimise toxic products and/or emissions to be formed, which can lead to air or water impacts as well as affect human beings, animals and plants. Recycling can have different meanings as can be understood from the examples above and a clear definition of the word is recommended to avoid misunderstanding in specific cases [49].

### 3.3. Market aspects and customer demands

All materials selection must be adapted to the customer demand. Materials for more prestigious and expensive products must usually be chosen according to the following points [36]:

- Generally use pure or carefully improved materials.
- Expensive raw materials or carefully worked materials with expensive and advanced processes are usually popular.
- Avoid synthetic polymers (plastics), because of its doubtful reputation as a cheap substitute material. However, plastics can be used if advanced and expensive additives like carbon fibres are used.
- Ceramics can be used.
- No fake materials are accepted.
- Natural organic and inorganic materials are generally popular like wood, silk, cotton and wool.
- Cheap materials can normally be used if advanced production techniques like ennobling or refining are used.

For cheap products almost any material can be used which is cheap, sustainable and does not need expensive production methods like advanced surface treatment or machining.

Note that there are always market trends, which make certain types of materials popular under a certain period. Light and dark wood comes and goes and we can see how early car bodies made of wood in the early 20th century have changed to steel ones and during the last decades to composites and aluminium. In the kitchen, we can see how pans have changed from cast iron, glass enamelling, stainless steel, surfaces coated by polymers or advanced ceramics. Some materials seem to disappear in products for good, like stones in axes, wood in big ships or natural guts for strings in tennis rackets. In these cases, more suitable and advanced materials have been outraging the old ones like steel in axes or ships and synthetic polymers for tennis rackets.

### 3.4. Dematerialisation and MIPS

The availability of materials for products will typically not increase in the future, as the amount of materials is limited. An exception could be wood where replanting trees actually can increase the amount of trees in a region or a country. This has happened in Sweden during the late 20th century. Anyway it is desirable (due to, e.g., sustainability and economics) to design a product in such a way that the use of the material will be limited. A useful way of minimising the materials used in products is to use a concept, which is called dematerialisation. Dematerialisation is a way to reduce the environmental impact per unit of economic input. Another definition of dematerialisation is the waste generated per unit of every material product [50].

The environmental impact per produced unit can also be weighted as the cradle-to-grave Material Input Per units of Services (MIPS). The MIPS also includes materials used directly or indirectly for energy input for a certain product [51]. This means that the MIPS accounts for all material and energy used along a products life cycle from extraction of materials until final disposal. The concept is however generally missing the flow of toxic substances during the life cycle of the product, which is a drawback.

### 3.5. Some general advices for more efficient use of materials

- Material substitution can reduce the environmental impact [52].
- Material efficient designing (dematerialisation) can be used. This means that as little material as possible is used. To obtain high strength in structural products, the Finite Element Method (FEM) can be used to optimise the strength of a product [53]. Another way is to use thin layers of rare or expensive materials like veneering of wood or plating noble metals on cheaper substrates.
- Composite materials can sometimes reduce the total amount of material used in a construction, because of the often better utilisation of the materials used [54]. However, it is generally more problematic to recycle mixed materials, i.e., utmost precautions must be taken when using composite materials.
- The materials selection and the product design should be done with the intention of future recycling of the material.
- Use MIPS (Material Input per Services) as described above.

### 3.6. Materials selection

Materials selection could be done in different ways, but the principles are quite similar. The selection of material is to optimise a product mainly with regards to the following aspects:

- Production methods.
- Function and structural demands.
- Market or user demands.
- Design.
- Price.
- Environmental impact.
- Lifetime.

Important situations motivating selection of material in a product as a whole or part of the product:

- Total new design.
- Improvements.
- Environmental demands.
- Delivery or supply problems for a material.
- Market demands.
- Adaptation to new methods for manufacturing.

Example of a common materials selection model based on specification of requirements is shown in Table 2, which is called a requirement property profile table:

In Table 2, we can see how product requirements are matched subsequently with the properties of possible materials. Materials 1, 2, 3 and so on are quite often the same type, e.g., different kinds of polymers or steel types. However, different kinds of material groups (like ceramics, metals and natural inorganic materials) can also represent materials 1, 2, 3, etc. In the example in Table 2, material 2 seems to be the best choice even if the price seems to be somewhat high. The total cost needs to be calculated for a special design, manufacturing method, etc. which means that a slight change in the design can change the price. The selection is typically an iterative process with subsequent optimisation. A slight change in design with some cooling might change the situation so that material 1 can be acceptable, which can result in a lower product price. Other examples are the use of qualification parameters to sort out unsuitable materials in an early stage. Qualification parameters can be used to select high temperature stable materials with low prices. This can be done by dividing the highest temperature for use with the price and maximising this value for possible materials. In this example it will be ($T$/€).

A material change in a certain product generally changes the design, in order to optimise the characteristics or the manufacturing methods for a product. A wooden chair has for example typically thicker legs to compensate for the reduced strength of wood compared to steel. Another example of the relationship between design and material is sharp radii, which typically gives high stresses for parts exposed to load. Ceramic materials are quite sensitive to high stresses in tension, which must be avoided by rounded inner corners in order to reduce the stresses. Metals, however, are typically less sensitive to tensile stresses and here sharp inner corners with small radii can be accepted in non-critical constructions with ductile metals. Hence, materials and design are very closely linked to each other.

Table 2
Example of 'Requirement property profile table' [42]

| Requirements for the product | Properties for material 1 | Result | Properties for material 2 | Result | Properties for material 3 | Result |
|---|---|---|---|---|---|---|
| $-40\,°C < T < 90\,°C$ (continuous service temperature) | $-50\,°C < T < 85\,°C$ | ? | $-40\,°C < T < 150\,°C$ | OK | $-50\,°C < T < 200\,°C$ | OK |
| Volume resistivity $> 10^9\ \Omega m$ | $10^{15}\ \Omega m$ | OK | $10^{10}\ \Omega m$ | OK | $10^{11}\ \Omega m$ | OK |
| Young's modulus > 1 GPa | 1,2 GPa | OK | 20 GPa | OK | 3 GPa | OK |
| Total cost per unit < 5 € per unit | 3 € per unit | OK | 5 € per unit | (OK) | 9 € per unit | – |
| Impact load > 20 | 25 kJ/m$^2$ | OK | 30 kJ/m$^2$ | OK | 22 kJ/m$^2$ | OK |

### 3.7. Sustainability strategies for design

In the last decades, many new concepts have been created to fulfil modern product development as well as environmentally friendly production like DFE (Design for the Environment) [55,42]. DFE can be seen as a broad and general concept for promoting a sustainable design. The concepts below are typically not standardised, but they are helpful in promoting emphasises in a certain sustainable direction. Some examples of common strategies in order to reach a sustainable design are [42,56–58]:

- *Eco-design*, which is also known as Design For the Environment (DFE).
- *Modular design*. Easy repair and change of components are here important. E.g., parts in copying machines and computers.
- *Design for material substitution*. Substitution of materials with high environmental impact to more superior materials in terms of sustainability.
- *Waste source reduction design*. Reduce the amount of material both in terms of the product itself and packaging.
- *Design for disassembly (DFDA)*. A product should be easy to disassemble with, e.g., snap fits, mechanical locks, etc. in order to recycle the materials.
- *Design for recycling (DFR)*. DFR focuses on maximum recycle-ability and a high content of recycled material in the product. Different materials should not be mixed if not necessary and different parts should be labelled for easy materials separation.
- *Design for disposability*. Assures that non-recyclable parts or materials can be disposed in an ecological way.
- *Design for reusability*. Focuses on possible reuse of different components in a product. The reused parts could be freshened up and reused.
- *Design for service (DFS)*. The design of a product is made here in order to obtain easy service from the outer regions.
- *Design for substance reduction*. Undesirable substances, which are used during the products life cycle, should be minimised.
- *Design for energy recovery*. The design here is made with materials suitable for burning with a minimum of toxic or harmful emissions.
- *Design for life extension*. Reduced waste through prolonged life for components or products is the aim of this strategy.

The concepts above are typically not standardised. Anyway, they are helpful in providing more sustainable products. The abbreviations in parentheses above are quite widespread and well known.

DFMA (Design for Manufacturing and Assembly) is an example of another well-known concept, which is not typically connected with sustainable design. DFMA is a concept that includes both DFM (Design for Manufacturing) and DFA (Design for Assembly) [55]. DFMA integrates the design process, which typically includes the selection of material, process planning, testing, assembly and quality assurance. It is a method for simple production, which can also provide a more sustainable production because of the attempt to use a minimum of production resources.

Another interesting strategy is to optimise a product with a multi functional design like a fax/copier/printer device or to design the product in such a way so as to increase the lifetime of the product as well as having service possibilities in a greater range [59–61].

## 4. The use of sustainable products

There are some interesting ways to obtain a more sustainable use of products. One interesting approach is to consider re-manufacturing of old products, which can be an interesting alternative to produce new ones. New products can have longer expected lifetime or a new design. However, there are models like the End Of Life (EOL), which can inform if it is an acceptable cost to re-use, recycle or dispose a certain part in a product or the whole product itself [62]. Case studies for product manufacturing are also a possibility to make decisions about manufacturing of certain products [63].

The use of sustainable products can be transferred to the producing companies rather than to the consumer. Today we are living in a world where service becomes more and more important in many countries. More than half of the total labour in many industrialised countries is involved in services like transportation, health, retail and wholesale distribution, social welfare, finance, etc. [64]. When the service is dominating in a country and the products are substituted by services, it is common to call this system as a *functional economy* or a *service economy* [40,65]. A change from the focus of producing and consuming products to a system where service components replace the more materialised focus can be a way to reduce the environmental impact of consumption. Such a service system is usually called a Product Service System (PSS), which is a way to reach a more sustainable development [66]. A PSS means that product producers will be responsible for delivery, guarantees, repair, upgrading, maintenance, take back, recycling, etc. [67]. An example of this is leasing systems for copying machines, coffee automates, etc. This is a way to let the producer or supplier take care of the environmental planning and to extend the lifetime of a product. The environmental benefits can also be a result of more intense use of products such as car or boat rental.

## 5. Integrated sustainable product development impact evaluation

In order to get as low environmental impact for a product as possible, a side by side evaluation of different products or ways of manufacturing is useful. The idea here is that a price must be set for every step in a Life Cycle

Assessment. Even the ecological impacts degree of equity must be set a price to restore the environmental impact and to get fair salaries for the workers. The main basic steps of an LCA as mentioned above (material extraction, manufacturing, packaging, transportations, product user stage and product disposal stage), generally have to be increased according to the specific product. For a sustainable product, a price can be set for every step, which can tell the price for restoration of the environment and the cost for equity.

Evaluation programmes (e.g., computer based) typically gives a certain numerical value for each step in the LCA. A numerical value is then a quite simple way to determine different materials, manufacturing processes, etc. with each other. Such programmes are generally developed by a team of experienced people who determine a certain impact in each step [www.ecoscan.nl].

As mentioned earlier a full restoration can never be obtained, hence, the total entropy for the earth will always increase when material products are made. This fact has to be kept in mind when the total cost for different products is compared. A quite problematic issue is to compare the cost for different environmental impacts. For example, how can waste of 1 kg toluene be compared with waste from 1 kg benzene or 1 kg $CO_2$ be compared with $SO_2$? If chemical substances are dissociated to harmless products like $CO_2 \rightarrow C + O_2$, the efforts (e.g., energy to support such a reaction) must be kept in mind. Are the 'efforts' to make carbon (C) and oxygen ($O_2$) higher than the environmental impact from $CO_2$? From what we know today, the environmental impact from $CO_2$ is much lesser when compared to the performance of the above-mentioned reaction when $CO_2$ is dissociated. If we compare toluene with benzene, we must always keep in mind that the environmental impact might not be fully understood today and the assumed degree of impact might be changed in the future. Only some decades ago benzene was seen as a quite harmless liquid used for cleaning, etc. but today we know that it causes cancer. Today, $CO_2$ is partly responsible for the greenhouse effect in the world.

How can, according to what have been said above, a reasonable cost then be estimated for a restoration of an environmental impact in practise? There are some common ways like regarding legislations, documents for sustainable production (like EMAS) or follow instructions from different marking systems like the 'E star', 'Environmental protection agency', 'EU-sign', etc. In fact for most companies the legislation is fulfilled and the minimisation of waste is often an issue, which is based on the lowest cost for the production or the use of the product. The steering from authorities is typically done in a way that environmental impacts are costly due to higher taxes for harmful wastes, etc.

The sustainable product development for successful products can also be simplified as a chain with important links, which has to be strengthened up as shown in Fig. 1.

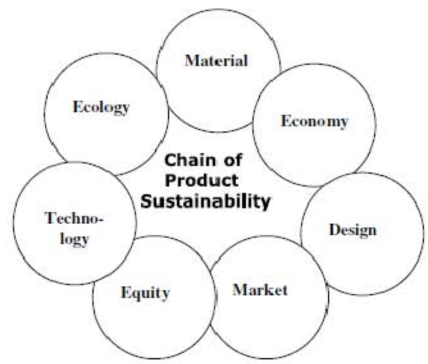


Fig. 1. Chain of product sustainability.

The seven rings in the sustainability chain circle, in Fig. 1, can be explained as follows:

- *Material.* Minimise the material use and try to use renewable materials. Minimise the energy consumption during the LCA and avoid toxic materials, etc.
- *Economy.* Product and service must be cost efficient and comparable with similar products. Consider the total cost during the life cycle including the cost for restoring environmental impacts. What about ownership, serviceability, PSS?
- *Design.* Design for the environment and the product user as well as for recycling!
- *Market.* Develop products and design them according to the needs from the specific market and target group.
- *Equity.* Is the trading equitable and what is the impact on the local and global community? What about employee conditions of work?
- *Technology.* Optimise the extraction of raw materials, production, lifetime and quality and functionality of the product.
- *Ecology.* Eliminate emissions and waste and minimise the environmental impact.

The product development can be simplified with the following steps:

1. Concept stage for the product.
2. Determine the life cycle stages (LCA) and calculate the total cost including environmental load.
3. Evaluate different products and the production step for each product side by side in order to minimise the environmental impact for the whole life cycle by optimising the sustainability impact.

Examples of databases for evaluation of environmental load and materials selection:

- www.ecoscan.nl. TNO Industrial Technology – Product Development, P.O. Box 6235, 5600 HE Eindhoven, The Netherlands.

- www.esm-software.com/mapp/ (ESM Software and ASM's Mat.DB databases, ESM Software Inc., USA).
- www.plaspec.com/web/qwMain (PLASPEC Materials Selection Database by Bill Communications Inc., USA).
- www.polymer-search.com/plascams/ (Plascams on-line plastic materials selection, Rapra Technology Ltd, England).
- www.stn-international.de/stndatabases/databases/pdlcom.html (PDLCOM by William Andrew Inc., USA).

## 6. Discussion

The availability of materials for products will not increase in the future, as the amount of material is limited. However, the resources of energy will probably be more critical in the future than the availability of materials and the relation between material and energy is quite obvious. A good designer and/or engineer must, e.g., be aware of these facts and be able to continuously look for new products where new materials and production methods can be used together with a sustainable design.

During only about two centuries, we have seen a development from an almost total dependence on an agricultural production through a rapid growth of manufacturing industries to a post-industrial era where service has been substituting many technically advanced products. We have observed a dramatic environmental impact, which has affected the whole earth including its life. The need of more products, which includes more fashionable and modern products, is still an unsolved issue in the sensitive ecological system we live in. A change to products with low environmental impact including longer lifetime and an end of the "Throwaway" society are examples of a society, which is not so easy to achieve. One reason for this is simply the fact that there will always be people with enough money who want to buy products regardless of the sustainability. Another problem is the poor people who just want to survive. For many people, the environmental impact is also more or less unimportant for different reasons. Even if there are sustainability directions like high taxes on fuel, some people still want to have big and powerful cars regardless of the fuel consumption. Legislation, which prohibits big cars, etc. is also problematic if it is not applicable for all nations. Political control of sustainability by legislation is often a balance, which is problematic in most countries. For example, too much control by legislation can easily result in massive actions from different groups of people and elections where new politicians with less interest in preserving the nature are elected. This is one of the great dilemmas for creating a sustainable society.

## 7. Conclusion

Over-consumption, resource utilisation, pollution and over-population are examples of the perhaps most basic problems for the environment in the future. A more sustainable future can be achieved by producing more sustainable products causing less environmental impact. Materials and design are and will always be very important areas when developing more sustainable products.

The Life Cycle Assessment concept might be the most effective way of determining the environmental impacts for all product stages from extract of material to the product disposal stage. A price must be set for restoration on every environmental impact. Information can be received from official authorities pertaining to the environment in different countries. Renewable and easy recyclable materials are preferably used together with a design for easy recycling and repair of the products. Minimisation of the energy connected to the product is also important. 'Full sustainability' can never be achieved for products according to thermodynamic laws. However, the attempt to achieve more sustainability is a requisite if we want to preserve the earth for the coming generations.

Education, research and spreading of information will be very important for the future in order to receive more sustainable products especially because the market demand is important in order to develop successful sustainable products.

## 8. Future visions

Optimisation of product sustainability by computer programs, as well as more educated and conscious people will be important for a sustainable future. New and more sustainable production methods will come into existence and it is important to be up to date with the new methods. Many new types of materials will also be presented, which demands for more experienced and trained engineers and designers. Adjustment to the market will be more and more important as well as informing people about the necessity for more sustainable products. A more integrated product development with the help of advanced computer programs including advanced Life Cycle Assessment will probably be more common.

The poverty among many people will still be a problem, which must be taken more seriously. Who wants to preserve rain forests and rare animals when it comes to a critical point, like getting food for a starving family? In the long run people will succeed in preserving the nature, but it is not easy to tell people in crisis about such issues.

Important things to do, in order to prevent the earth from an ecological collapse in the future, are to:

- Increase the knowledge among people, of what it means to live in a sustainable way. This can be done by education in schools, spreading information in articles, seminars, mass media, etc.
- Have political control and support sustainable companies. Waste and emission control of toxic products, etc. can be done by legislation and taxes.

- Spread the knowledge among people that the world is unique and need to be preserved also for the coming generations.
- Buy more sustainable products and support companies with ecological aims by buying their products.
- Increase the research and development of more sustainable products.

This paper is one example of spreading increased knowledge of how to use materials and design in order to create more sustainable products.

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3. Artículo: Marco integrado para implementarse durante el desarrollo de un producto sustentable. Desarrollado por: Sami Kara, Ina Honke y Harmut Kaebernick.

# An Integrated Framework for Implementing Sustainable Product Development

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## Abstract

*This paper presents an integrated framework to implement Sustainable Product Development (SPD). The focus is on integrating environmental sustainability in manufacturing firms with control over key product development processes, particularly the early phases, since they are the key players in designing and manufacturing products. From an analysis of the best available developments by researchers and industry, appropriate tools and activities are linked to three implementation levels as enablers for implementing SPD. The proposed approach combines strategic and operational approaches in a single framework. The aim of linking tools and activities to different implementation levels differentiates the proposed framework from other less comprehensive approaches.*

**Key words**: Sustainable Product Development, Strategy Planning

## 1. Introduction

The importance of environmental sustainability and Sustainable Product Development (SPD) was first acknowledged in 1987 by the "Bruntland Report" [57, 81]. The second milestone was the launch of the eco-efficiency concept in 1992 [97]. All of these efforts aim for "creating more value with less impact" and set the new focus on creating environmental and economical benefits throughout the product's life cycle. It has been widely accepted that the successful implementation of SPD pays off in terms of improved corporate image, financial profits, and competitive advantage in the market.

However, the implementation of SPD is a challenge for the manufacturing industry. As a result, the improvements have been small compared to what could have been achieved [7, 40, 82].

Literature suggests that there are three areas of SPD implementation, which need further attention in order to achieve the expected benefits. These are the applicability of actual operational concepts, the development of strategic SPD concepts, and the interactions between strategic and operational concepts [5, 56]. Many researchers conclude that the actual concepts are neither related to a general framework nor presented compatible to each other or to traditional product development methods [40, 75, 95]. Furthermore, they discovered that strategic approaches are crucial to implement SPD successfully in the long run, but the field is rather underdeveloped [5, 12, 56].

## 2. Methodology and concept

The proposed framework was developed as a conclusion of an analysis of successful SPD implementation cases and best practices around the world as well as the literature published in this area in the last couple of decades. Incorporated best practices are publications of companies from all around the world and of different branches, e.g. Henkel Group, Interface Flooring Systems, Philips, SC Johnson, Sony. Since pilot projects represent too small a sample to develop a broad understanding of the field, the study adopts a qualitative literature review. The field is unattainably by designing and statistically testing of specific projects. The mere examination of SPD projects is occasionally adequate to explore underdeveloped areas. Strategic SPD approaches are an area where best practices are adapted and generalised for the provision of required concepts.

The analysis of successful implementations indicated that the differentiation of the approaches is needed at three organisational levels, namely the strategic, the tactical, and the operational level. In addition, each of these organisational levels is characterised by a different set of features for implementation and also requires different tools and methodologies to be applied. From the analysis of best practices and the literature, five features have been identified as critical conditions for a successful implementation. The five features include:

1. Environmental AIMS – Strategic SPD defines the business objectives towards environmental sustainability and therefore integrates the environmental consciousness into the traditional business leading to long term success. The significance has increased only recently and the literature is fairly scarce [12, 56].

2. Environmental PERFORMANCE – Effective SPD is carried out in the daily business of the product managers, considering the entire Life-Cycle of the product. Life-Cycle Assessment (LCA) is a basic concept to operationalise SPD.

3. EARLY stages – Modern methods focus on the early stages of product development intended to realise more innovative and cost effective solutions.

4. Top-down and bottom-up IMPLEMENTATION – Only the combination of strategic guidance and operational activism from the designers ensure effective SPD implementation. As a conclusion of this double track, the strategic content and intent is linked towards integrating SPD most effectively within the entire organisation.

5. Specific and general SIMPLICITY – Enabling methods and the framework are required to be simple enough for the users to apply, from the designers to the management. The term "simple" is used in the meaning of manageable and applicable.

## 3. The Integrated Framework

From linking enabling tools and techniques to the different implementation levels, the framework is formed, as presented in Figure 1. Hence, the framework contains concepts to support a company constituting its environmental strategy (level 1), concepts for tactical decisions considering the entire product Life-Cycle and for efficient internal communications (level 2) and operational concepts to integrate the environment as an objective into the traditional product development process (level 3).

On the first level, the methods associate the first feature with the fourth and fifth. As a result, the aim is at systematically developing and applying the environmental goals to the corporate culture. On levels two and three, the concepts are developed out of the grouping of the second to fifth features. The mutual focus is on an effective environmental performance (feature 2) with the emphasis on the early stages (feature 3). Furthermore, whereas the enabling methods of level three enforce bottom-up approaches, the second intersectional level intended to ensure the efficient linkage of the bottom-up ideas and the top-down strategy. Both levels entail enablers to integrate SPD into the conventional product development operations, either more managerial (level 2) or practical (level 3). Therefore, a joint section describes the enabling techniques with regards to their minor differences.

Finally, it becomes apparent that this simple structure meets the fifth feature accordingly. Due to the basic validity of the fifth feature, it is integrated at each level. In order to give consideration to the smooth transition of top-down to bottom-up approaches, the fourth feature is overarching all levels. Therefore, both features are utilised as rule of thumb for all organisational levels, which are required to meet their conditions.

## 4. Enabling Methods

From the analyses of the literature and best practices, enabling concepts and activities are selected and clustered in nineteen main areas towards implementing environmental sustainability into the manufacturing industry. With including the given references in the Figure 1, the framework facilitates the detailed study if desired.

### 4.1. Level One

Suitable concepts enclose strategic SPD theories, techniques evolved from best practices and an administration system. In total, seven main areas of methods have been identified. Based on the strategic SPD literature, the first two approaches enable the comparison of the existing business strategy with others on the market or standard strategy types and thus enable the defining of the individual one. The next four concepts are mainly designed from best practices. These applications stress the question of how to embed the sustainable aspects within the organisation. Examined best practices showed mutual patterns of answers concerning the integrated four principal areas. Finally, the environmental management systems assure the computer-based, consistent documentation and evaluation of the Ecodesign activities aimed at checking the suitability of the SPD strategy in the long term.

Therefore, the concepts enhance the environmental strategy creation (methods 1 and 2), the establishment of the inherent objectives within the firm's structure (methods 3 to 5), and finally the consequent administration (methods 6 and 7). By applying them, the concepts assist the strategic management in creating the firm's environmental policy with the most potential in the market and embed it top-down in the organisation leading to a long term success.

| | | | |
|---|---|---|---|
| *Levels of Implementation* | ***Level 1:* strategy**<br>• developing and constituting the environmental strategy<br>• focus: corporate level<br>• users: senior management | ***Level 2:* tactics**<br>• tactical decisions considering the product Life-Cycle and interrelations<br>• focus: product dev. process<br>• users: product manager | ***Level 3:* operations**<br>• hands-on concepts to integrate SPD into the traditional product dev. process<br>• focus: product dev. process<br>• users: designers |
| *Features* | • environmental aims<br>• specific and general simplicity<br>top-down approach → | • environmental performance<br>• early stages | • specific and general simplicity<br>← bottom-up approach |
| *Enabling concepts for Imeplementation* | 1) Env. Benchmarking [44, 49, 85]<br>2) Env. Strategies [8, 25, 38]<br>3) Env. Action Plans and Champions [12, 14, 25, 26, 68, 76, 84, 85, 86]<br>4) The Integration into the Organisation's Structure [12, 22, 20, 76]<br>5) Education Programmes [12, 24, 26, 76, 84, 87]<br>6) Env. Auditing [9, 12, 19, 76, 77, 78]<br>7) Env. Management Systems [2, 4, 12, 14, 32, 33, 34, 42, 43, 58, 66, 91] | 1) SPD Process Declaration [60, 86, 92]<br>2) Communication Systems [21, 76]<br>3) Advanced Env. Systems [3, 12, 16, 17, 18, 25, 29, 59, 62, 73, 76]<br>4) Life-Cycle Assessment [6, 8, 42, 60, 98, 99] see methods 7 to 11<br>5) Environmental Accounting [10, 13, 28, 61, 64]<br>6) Multi-Criteria Assessment concepts [36, 47, 48] | 7) Indicator concepts [21, 35, 41, 46, 65, 74, 103]<br>8) Environmental Quality Function Deployment [36, 37, 55, 79, 80]<br>9) Environmental Failures Method and Evaluation Analysis [51, 52, 71, 72]<br>10) Matrix concepts [1, 8, 49, 50]<br>11) Checklists [8, 12, 25, 27, 54, 70, 71, 72, 76, 83, 86, 94, 100, 101, 102]<br>12) Creativity Techniques [12, 14, 24, 25, 45, 50, 86] |

Figure 1. The integrated framework

## 4.2. Levels two and three

Many theories and cases provide appropriate principles aiming for effective set up of the environmental design operations. For both levels together, twelve enabling methods have been defined.

Tactical concepts support the product development managers to assure the adequacy and suitability of the environmentally sound products and design processes, as well as to communicate between the strategic and operational level. At first, the method one provides the understanding of efficient SPD processes and thus the ground work for the decision-making on SPD operations. Secondly, the purpose of the computer-aided systems is to fulfill the function of an efficient communication channel and assure the adequacy and reliability of the environmental assessment. Integrated approaches easily interface with the users on all three levels and thus provide the desired function.

Area three of tactical methods addresses the important field of analyses and contains approaches of assessing the impacts on the environment (methods 4, 7 and 11), and evaluation concepts regarding complementarily economical (method 5) and quality concerns (method 6) along the product Life-Cycle. For the purpose of the proposed framework, the use of a full-scale LCA is neither efficient nor compulsory for every SPD process and thus essential simplified, quantitative (method 7) and qualitative (method 11) techniques are described. Further analyses, either environmental accounting or multi-criteria assessment, present a high complexity and therefore are scarce at the early stages. For the purpose of the framework, most effective attempts are selected from the literature, as the integrated Life-Cycle Costing (LCC) and LCA methods, End-Of-Life costing, abridged LCC systems, and three combined QFD, LCC and LCA approaches, i.e. two conceptual and one computational.

Further effective tools then convert the communicated tactical goals and the designer's practical ideas into a sustainable product or service. The focus is on easy applicable design improvements and environmental idea generation methods with the intended use at the early stages. Therefore, operational SPD tools entail semi-qualitative (methods 8 to 9) to qualitative design tools (methods 10 and 11) and environmental creativity techniques (methods 12). These suitable tools tend to integrate environmental concerns of designers and other stakeholders most efficiently into the conventional product development procedure. With integrating the many tactical and operational tools and techniques available in the literature, adequate guidance for the product managers and the designers is given within the framework in order to promise SPD real. Both, product managers and designers, apply these analyses tools. While designers generally utilise their outcome in terms of indicators or rules of thumbs, managers have an understanding of the methods' basic principles and make the detailed analyses. For both parties, the methods support their decision-making in order to provide an excellent and environmental performance in the product development processes.

In conclusion, all levels are well defined and sufficiently fulfill the required sets of features. With consideration to the fourth feature, it can be said that the top-down and bottom-up implementation is enabled to the extent that strategic advice and operational tools are adequately provided. In the face of accomplishing the fifth feature, the methods' selection and the concise presentation ensures the straightforward applicability by the addressed users. Therefore, the use of the framework leads to a successful integration of environmental sustainability in manufacturing firms. Most success is promised by beginning the application either at the first or the third level. The second level does not represent an effective starting point as it requires the consideration of up- and downstream activities at the same time [11]. As a result, neither the first nor the third level is more advantageous to start with the SPD implementation. The decision is characterised by the amount of resources and time available at the beginning of the implementation process. With the methods and features given, the implementation from the first level requires resource-intensive activities and a long-term commitment. In order to start with the implementation at the third level, fewer resources are initially needed and the results affect the product development simply in a short-term. The implementation chain follows then either downstream or upstream within the organisation.

## 5. Conclusion

An integrated framework for implementing Sustainable Product Development (SPD) was developed and presented. The proposed concept is appealing as an essential means in guiding manufacturing firms systematically to integrate environmental sustainability with enabling concepts and techniques. The developed framework includes five features, a three level structure and appropriate tools and activities. The methodology and the five features have been designed from the analysis of the successful SPD implementation cases and the available literature in the last decade. Key elements of the framework are SPD concepts that support strategic planning on the corporate level (level 1), tactical decision-making and inter-organisational communications (level 2), and practical designing (level 3).

The developed matrix differs from the previously published approaches by combining both strategic and operational concepts in a single framework towards establishing SPD in a manufacturing environment. In addition, the functional clustering of appropriate tools and activities related to each implementation stage ensures the straightforward applicability by the users and complements the SPD integration.

The field of actual SPD tools is rather wide and ambiguous as it consists of general to specialised approaches that concentrate on the operational rather than strategic level and are presented complementary, sometimes contradictory to each other or conventional product development concepts. Due to the scarcity of literature and complexity of the strategy level topic, the strategic methods appear fairly empirical and require more field-testing and standardisation. Likewise, previously published attempts to structure them concentrate merely on the design processes fall short of enclosing both the tools for developing sustainable products and a sufficient systematic approach in an attempt to provide a universal framework. There is a further need of appropriate and comprehensive clustering of methods for the systematic SPD integration. Furthermore, research is required in the areas of multi-objective concepts (tactical methods 5 and 6) with the intended use in the early stages and the methodological support of embedding bottom-up approaches with enabling operational tools. The latter is mainly due to the fact that the incremental ideas are initiated by motivated designers and relies on their individual enthusiasm. Therefore, the focus should be to a greater extent on research of the multi-criteria assessment concepts.

Through the use of the proposed approach, manufacturing firms are provided with a general platform towards implementing SPD with enabling tools and activities. Experienced research contributes to the work by supplementing approved methods to the conceptual structure. With regard to the required fifth feature, the inherent flexibility allows an efficient extension of the integrated concepts in numbers while having consistent regards to all five conditions.

However, the proposed approach does not take into account the role of external factors, such as public policies, social principles, product and company specifics, and supply chain characteristics. Further research needs to be carried out on how to incorporate these factors into the developed framework, which would be a useful extension to this project.

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4. Artículo: Implementación de procedimientos para el desarrollo de productos sustentables en PYMES utilizando tecnologías disponibles. Hecho por U. Woy, Q Wang.

# NEW PRODUCT DEVELOPMENT: IMPLEMENTING PROCEDURES FOR SUSTAINABLE PRODUCT DEVELOPMENT IN SMEs UTILISING AVAILABLE TECHNOLOGIES

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Keywords: NPD, SMEs, technology management, personnel, sustainability

## Abstract

Small to medium sized enterprises (SMEs) in the UK are increasingly engaging in new product development (NPD) for competitive advantage. With limited resources and expertise in new product and process development, introduction and implementation the associate risks are significantly higher for those involved. In this paper, Enterprise Resource Planning (ERP) Technology is used to provide an insight into the relationship between technology application, personnel involvement and sustainable product development in a sub-contract manufacturing SME. The aim is to provide a product development strategy supported by the implementation of sustainable product development procedures through the utilization of available, advanced technologies.

## 1 Introduction

Manufacturing small-to-medium sized enterprises (SMEs) in the UK regularly experience fluctuations in the market, which creates an adverse effect on the number of businesses in the sector. For SMEs operating in the current business environment, survival in what has become an even more competitive sector, is often a challenge. This is not a unique situation to the UK as SMEs in other countries compete in an equally competitive market [**10**]. There are a number of internal and external factors that have contributed to the current state of affairs. Nevertheless, SMEs can still achieve business excellence and improve their economic future by diversifying.

New product development (NPD) and introduction is recognised as a suitable diversification strategy for SMEs, 'and emphasis is being placed on systems which simultaneously provide quality, variety, frequency, speed of response and customisation' [**1**]. These systems combined with proper planning, implementation and management of NPD strategy, processes, activities and related issues [**4, 7, 8**] help to mitigate some of the associated risks.

The successful execution of a product development process requires the efforts of a cross-functional team, concurrent engineering, advanced tools, early involvement and other internal mechanisms, which can be challenging for most SME [**1**]. External mechanisms such as the socio-cultural environment, government support, access to advanced tools, marketing expertise, availability of skilled labour, supplier relations and so on, also influence the process [**2, 10, 12**]. Advanced technological tools like enterprise resource planning (ERP) are capable of integrating both internal and external mechanisms and can facilitate the integration and reconfiguration of the NPD process, harness resources and expertise and co-ordinate the product development activities.

Using available technologies can greatly enhance the product development process for SMEs. Computer aided design (CAD)/ product modelling tools are now more affordable and can be used by SMEs to create realistic product models, a marketing strategy employed by industry leaders in the early stages of NPD before committing further resources. Other technologies such as rapid prototyping, finite element analysis (FEA), failure modes effects and analysis (FMEA) and other quality tools are used in the verification and optimisation of new products to ensure their success. SMEs require these tools, which are used by the experts and industry leaders. With government support through the introduction of several schemes to encourage innovation, companies can seek expert opinion and gain access to state of the art technological tools to achieve the desired success. The implementation of sustainable procedures for product development is achievable as SMEs now more than ever have access to the technology available to industry leaders.

## 2 Product Development in SMEs

### 2.1 New Product Categories and Development Strategies

There are two main categories that SMEs diversifying into NPD belong; those that proactively develop new products (the industry leaders), and those that adopt a reactive strategy to product development [**10**]. The setting of clear and realistic objectives, which are part of the company's overall business strategy, is characteristic of the industry leaders. The second category on the other hand, does not often begin in this manner or have the opportunity to consider all the factors that influence the development process. Categorising products at the start of the NPD process is useful when setting objectives and identifying a suitable NPD strategy. There are several criteria which can be used to categorise products but in this instance, the market, level of product innovation and market positioning have been used (Figure 1) as most companies set objectives based on one or a combination of these criteria.


Figure 1: New product categories

| Description of new product categories | |
|---|---|
| **Category** | **Description** |
| 1 | Radically new products that create new markets with very high level of product innovation resulting in a very strong market position. |
| 2 | New product in an existing market with very high level of product innovation. |
| 3 | Product line extensions are effective and innovative ways to reposition a company in the market place |
| 4 | Superior products in existing market attract higher costs, potentially generating larger profit margins from existing market |
| 5 | Existing product in a new target market to strengthen market position |
| 6 | Existing product established in an existing market place |

Table 1: Description of new product categories

Table 1 is a description of the main product categories identified in the market today. The more highly innovative a product is, the greater the associated NPD risks; requires greater resources, micromanagement and high levels of expertise. For less experienced companies, expertise and resources can be built up in a lower product category, which is less risky. This and other practices, such as information management, goal setting, vision support and NPD procedures that support team learning and their impact on speed to market and new product success **[6]** is critical to sustainable development.

Typically, new products are developed or reactively by companies. The main deference in strategy is that the former requires greater resources and investments than the latter. A reactive strategy may be more suitable for SMEs, because they can reap the benefit of developing a new product based on proven technology without the burden developing the technology themselves. Regardless of the strategy, every effort should be made to ensure that the timing is right for new product introduction. There are seven main stages in the product development process, shown in Figure 2 below. Experts and industry leaders employ techniques like the stage gate process and concurrent engineering, designed to reduce the NPD cycle time and progress a wider portfolio of new product opportunities through development to launch. **[1]**.

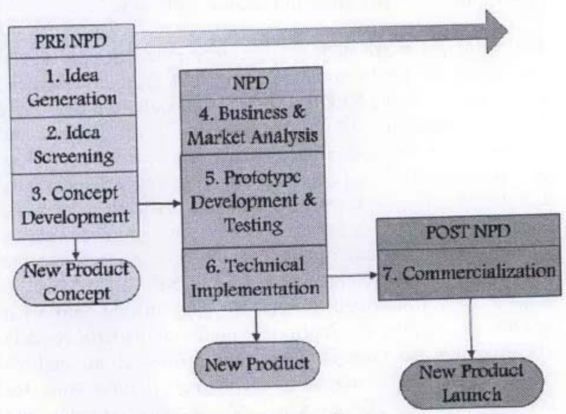


Figure 2: Stages in the product development process

For most SMEs, their approach to NPD is informal but four distinct stages; idea generation, concept development, prototype development and commercialisation are used by those with experience for the flexibility it gives and a faster time to market **[6, 10]**. However, SMEs often rush the already shortened process, developing the first concept generated and following it through to commercialisation. Nevertheless, the best strategy for successful product development is one that completes all the steps in the NPD process **[9, 10]**. The allocation of resources is required for this to be most effective and it is during this time that available technology plays an important role for SMEs.

## 2.2 Managing Personnel, Technology and Quality in NPD

NPD and other change mechanisms that result in the transformation of the typical practices of a business is often the reason for personnel development **[3, 13]**. However personnel training and development is usually reactive to newly implemented strategies or technologies, leaving the work force inadequately prepared. Also, there is a tendency for companies to pay more attention on the utilization of technology for business innovation than there is on training personnel to use the same technology effectively. NPD is a process employed by companies for business innovation that works best with cross-functional teams, with each team providing the necessary expertise for the completion of a product development project. 'Research has shown that effective integration of R&D, manufacturing, and marketing in NPD teams can enhance project performance and firm competitiveness' **[11]**. This is largely due to the fact that 'positive' routine behaviour develops selective attentions, which is responsible for the identification of indications that would be missed by the untrained eye [1]. However, positive routines cannot be established if teams are not adequately trained and motivated to become skilled at their tasks, which also encourages them to be innovative. Training, motivation and establishing positive routines can facilitate the realisation of NPD objectives for companies by harnessing the expertise of an integrated, motivated and innovative team to maximise efforts, increase efficiency and reduce cycle times.

Technological tools such as computer aided design (CAD) and computer aided manufacturing (CAM) have now become pre-requisites to the NPD process. Other tools like Enterprise resource planning (ERP) used in the management and integration of business processes are fast becoming business pre-requisites as they provide greater control, accountability and traceability over internal business influences and the capacity to adapt to external influences in a constantly changing business environment. ERP systems facilitate the integration of business processes such as NPD and SMEs can analyse data from such systems to gain insight into what products to develop by identifying trends and patterns for data classification. Accurate data is required for such an analysis to be an insightful source of technological innovation for companies, hence the emphasis on personnel training and development. Technology by itself does not bring about innovation nor does it give companies the competitive advantage they seek. It is the combination of the application of the right technology and personnel skills and expertise to business processes that makes them unique.

Quality is linked to NPD through cost and functionality, and there are several factors, including the industrial sector and the final application of a product that influence a customer's decision to buy a product of high quality regardless of the cost. For such customers, high quality demands high traceability, a good reason to implement an ERP system. Quality in SMEs is usually weighed against the costs involved especially because of the competition they face from companies with lower operating costs. Typically, companies will work to customer specifications and where none has been provided, they will usually work to meet the minimum quality requirements to keep costs down. However, there are company's that have implemented and continue to adhere to standards, which encourages team members to pay more attention to personal and team development towards a common goal. It might be expensive to adhere to quality standards initially, but cheaper in the long term once it becomes an established culture thereby reducing errors and critically, delivering customer products on time, within budget and to a high quality. This is important to NPD process and should be especially focused on if the company has not formally implemented quality standards. Nevertheless, for companies that chose to implement quality standards for their product development activities, it is shows commitment and gives customer added confidence in their capability to produce quality designs to the specified standard.

When developing new products for a target market, companies should make an effort to understand the requirements of that market. A suitable method for ensuring quality in NPD is the Quality Function Deployment (QFD). This is a recognised technique used by companies to understand the requirements of an industry through a translation of the functions of the particular product being developed, and interpreting it into an engineering specification that accurately captures the voice of the customer. Quality-Cost-Delivery (QCD) unlike QFD is a business function focused on lean manufacturing practices. It is a measure that companies employ to manage internal business processes and activities to identify key performance indicators (KPI) for business improvements. Using QFD and QCD to capture and implement product and process quality, companies engaging in NPD activities can effectively manage and monitor and maintain the quality of new products during and beyond the development process.

# 3 Case study of an SME

### 3.1 Background

Dyer Engineering Ltd. is a successful general mechanical engineering SME in the North East of England, specialising in low volume, high turn around parts. With over 30 years experience the company has successfully provided subcontract engineering services to a diverse range of industries in the manufacturing sector. Driven by the growth of the business and customer initiative, the company installed its ERP system, EFACS in 1999. EFACS is an integrated manufacturing, financial and distribution software and currently manages data on over 4000 live parts at any time and the production of about 30,000 parts per month for over 500 customers from a range of industries. As Paul Dyer, the managing director said, 'it's simply humanly impossible for anyone to keep on top of all that information…' In 2004, the company made a strategic decision to diversify its customer base and enter new markets by developing and introducing new products. The company is ISO 9001-2000 certified for the provision of subcontract manufacturing services and repairs to machinery and equipment but is not certified for 'Design and Development' activities.

### 3.2 Methodology

The case-study methodology has been shown to be effective in analysing NPD issues within small manufacturing companies [5]. This was used to understand the relationship between technology application, personnel involvement and sustainable product development during the product development process and the introduction of NPD Procedures.

The 'modular stillage system' a new product for the company was developed for a customer. New to the process, the company wanted to adopt a formal approach to product development and approached the University of Durham for support and expert guidance through a formal NPD process. The company required support in the development of this product and through this activity, introduce a product development process.

In order to develop a suitable procedure for implementation, each stage of the development process was recorded in a manner similar to the 'stage gate' process, where the management was required to take a decision before proceeding to the next stage. The recorded data was made available to the management as word documents, which were considered inadequate for the transfer and retention of the knowledge and experiences gained from completing each process. Furthermore, the management considered the process too slow and not responsive enough to match the fast pace of its made-to-order (MTO) business. But with limited resources and expertise to contribute to the process, the company went along with the product development plan. However, there was every indication that the company would revert to applying an informal approach to product development as this suited its needs better. Consequently, any procedures implemented as a result of the original NPD exercise would be viewed as temporary solution and not be successful in the long term.

Considering that the purpose of the project was to introduce a product development procedure, a solution that was suited to the companies needs had to be sought. EFACS has often been referred to as the central nervous system of the business, and seemed to be the key around which a solution should be developed to ensure that an adaptable NPD process could be implemented for and sustained by the company.

### 3.2.1 Incorporating NPD to a MTO Business

A research into the NPD process of SMEs in far eastern countries [10] revealed that SMEs that are traditionally made-to-order (MTO) businesses like Dyer engineering, follow the informal four stage approach to NPD. The company wants to remain a MTO business but incorporate NPD to strengthen its market position and protect its economic future. One of the characteristic of MTO businesses is their dependence on maintaining close customer relationships to ensure that there is a steady flow of orders for business continuity. While product development is dependent on the identification of new business opportunities through the recognition of market needs, which the company can fulfil. The risks with NPD are obviously greater as there are no close individual customer relationships but instead, a relationship with a group of customers is formed. There are also risks for SMEs depend on close customer relationships, if a breakdown occurs, especially if a few customers bring in a huge proportion of the company's profits.

The main challenges faced were in the identification of a suitable method for integrating NPD with the provision of MTO sub-contract engineering services without compromising on product quality; and changing the routine business operations and practices to accommodate the NPD process. Having identified EFACS as the key to any solution developed, an investigation of the system was carried out to determine the relationship between the system, the company's business processes and process teams, which would be central to the implementation of sustainable product development procedures. Figure 3 is a basic overview of EFACS.

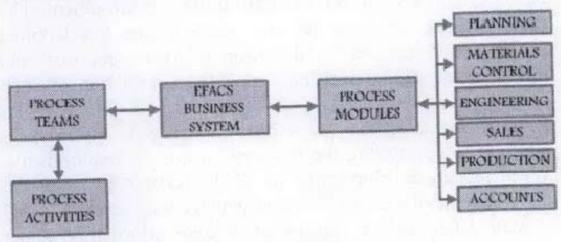


Figure 3: An overview of the ERP business system EFACS

EFACS manages the processes, the process teams who manage the process activities of the business. The process teams input data from process activities into EFACS via process modules, which are integrated internally. In this manner, EFACS supports and sustains the business processes, and process teams efficiently and effectively. Although EFACS does not have a specific NPD module, existing modules can be used to ensure that the process is integrated with other business processes. The existing business processes integrated by EFACS, and the product development processes were mapped in Figure 4, to understand the relationship that exists between the company's process and the NPD process.

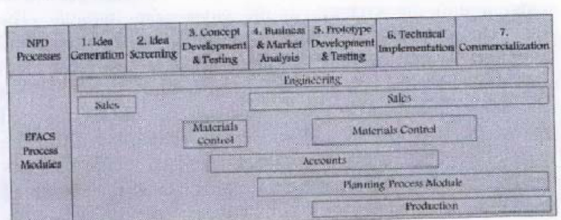


Figure 4: Mapping NPD and EFACS processes

The result of the mapping process supports theory that more resources are required in the latter stages of product development as opposed to the time consuming nature of the initial stages. Having established the relationship between

EFACS and the NPD processes, teams could be assigned to different stages of the process, reducing the time required to complete the process. Early involvement is critical to the NPD process but the right teams have to be involved at the right time. The company has a limited engineering and sales team therefore, it was not just a case of involving the team but ensuring that their time and expertise was maximised. Because EFACS already holds vital information, which has been collected over time, it was useful to begin the process by analysing the sales and engineering databases. From the sales database, customer details were obtained and used to identify potential industrial sectors to target. When the sales team was finally involved, their task had been simplified to identifying customers within the target sectors. With their knowledge about the customers, generating a list of criteria for creating a short list of customer to approach for prototype development and testing was completed in a fraction of the time and critically, the sales team was able to carry out their normal business functions in the normal business environment. The same process was used at each stage of the development process, with the team only meeting when necessary and management taking decisions upon the completion of each stage.

EFACS manages the parts bill of materials (BOMs) in addition to controlling the materials resources requirements. With recent developments in CAD technology and the development of the product data management module, CAD system databases are capable of holding information about product BOMs, allowing companies to successfully integrate their CAD and ERP systems. With the integration of CAD and EFACS, companies can successfully manage product quality and sustain the development of new products through the implementation of design and development standards. This impacts the manufacturing and other related practices that are sustained by EFACS.

### 3.3 Implementing the NPD procedures

To implement the NPD procedures, a separate document was created for every completed stage, to retain the knowledge for the company. One of the procedures implemented, is the procedure for supplier related activities. During the product development process, materials have to be specified for production during the concept development stage and this is entered into the system via the engineering module. The materials control team with knowledge of materials and suppliers, select the most suitable suppliers and enter them into the system as potential suppliers (Figure 5) and could at this stage, ask them to provide a quotation for the required materials. This information and other factors that affect the cost of production are used when conducting the business analysis to determine the best supplier based on the stored quotation data and negotiate contracts accordingly.

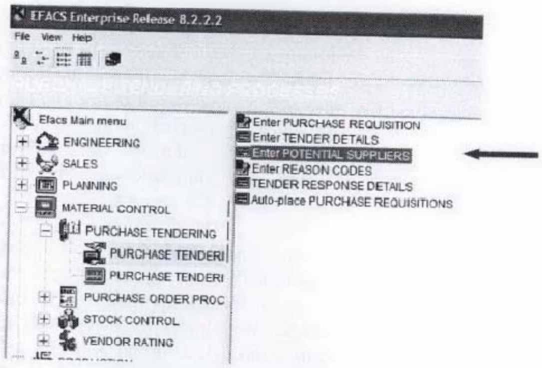


Figure 5: Implementing procedures for supplier activities

The other procedures were implemented similarly by using the existing relationship with EFACS processes to ensure that data was retrieved, analysed and integrated with a related NPD process.

An investigation into best practices for product development was carried out and documented at every stage of the process as this encourages companies to focus on implementing quality procedures at the initial stages of NPD. The benefits include meeting the needs of the customer, minimising costs involved and delivering high quality products. However, without a formal standard, encouraging staff to adhere to procedures is challenging and there is only so much that can be done to maintain quality in future NPD projects. Nevertheless, the company can demonstrate its commitment to sustainable development of quality products by adding 'Design and Development' activities to its ISO 9001-2000 certification.

## 4 Conclusion

SMEs have the potential to be innovative and competitive enough to survive in today's competitive manufacturing environment. But the responsibility lies with SMEs to source, obtain and retain the knowledge and expertise required to successfully develop and introduce new products.

The case study revealed that even though a collaborative team effort is required during the product development process, this is still a challenge for SMEs due to a lack of resources, expertise in NPD and a commitment to the process by top management and company staff. Even when teams were willing to partially commit to the process, management and existing customer priorities did not allow for this. The availability of advanced technologies through several government schemes designed to promote and stimulate growth and development within SMEs gives them an opportunity to take advantage of available expertise. This supports the development of positive routine behaviours that stimulate innovation. However, the management should be willing to commit fully to the process and encourage their staff to do the same before taking advantage of such opportunities, to experience their full benefits and achieve business excellence. Furthermore, there were several changes taking place at the same time and while this was all focused on company improvements, a lack of strategic foresight in the change process meant that already stretched resources didn't have enough elasticity to take on NPD at the same time. This affects the sustainable assimilation new knowledge, skills and expertise during the development process. Furthermore, changes implemented are not adhered to and this is critical to changing the company's culture through the assimilation of new knowledge.

Implementing NPD procedures using EFACS provides the best strategy for sustainable development in SMEs due to its data management capabilities. It facilitates knowledge transfer and retention, maximises available resources and reducing the burden on the requirements for resources. Personnel involvement is important to developing and implementing new processes and managing data. Therefore, regardless of the functions of a team, SMEs should strategically develop the right skills and expertise within the business by transferring new knowledge between available experts and company staff at all stages of the NPD process. During this process, best practices should be adopted and quality standards implemented and adhered to till it becomes a part of the company's culture. Combined with the right technology, implementing sustainable NPD procedures becomes easier and adaptable as the company becomes more innovative in its approach.

There is a lot of research available on the implementation of ERP systems, especially in the area of customer relationship management (CRM) and supply chain management (SCM). Other research developments include the integration of CAD and internet applications with EFACS. The implementation of NPD procedures could benefit from research into the introduction of a product development module within ERP systems.

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5: Artículo: Diseño modular como soporte de Ingeniería de ciclo de producto verde.

Desarrollado por Hwai-En Tseng a,*, Chien-Chen Chang b, Jia-Diann Li A

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# Modular design to support green life-cycle engineering

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**Abstract**

The severe competition in the market has driven enterprises to produce a wider variety of products to meet consumers' needs. However, frequent variation of product specifications causes the assembly and disassembly of components and modules to become more and more complicated. As a result, the issue of product modular design is a problem worthy of concern. In this study, engineering attributes were added to the liaison graph model for the evaluation of part connections. The engineering attributes added, including contact type, combination type, tool type, and accessed direction, serve to offer designers criteria for evaluating the component liaison intensity during the design stage. A grouping genetic algorithm (GGA) is then employed for clustering the components and crossover mechanisms are modified according to the need of modular design. Furthermore, a reasonable green modular design evaluation is conducted using the green material cost analysis. According to the results, adjusted design proposals are suggested and materials that cause less pollution are recommended to replace the components with pollution values higher than those in the module. Finally, the authors use Borland C++ 6.0 to evaluate the system and clustering method. To illustrate the methodology proposed in this study, a table lamp is offered as an example.


*Keywords:* Modular design; Green life-cycle engineering; Grouping genetic algorithm; Liaison intensity; Green analysis

## 1. Introduction

Not until recent years have people realized the importance of environmental protection. People pay more attention to the environment they are living in and the way people deal with the limited resources. Among resource disposal methods, recycling and garbage classification are two methods widely applied. These ways, however, are passive methods in the launch, usage and damage of products. Moreover, fierce market competition is shortening the product life cycle and the passive resource recycling approach can no longer cope with the ever-increasing burden current products have on the environment. Therefore, it is important to maximize the usage percentage of resources and minimize the damage to the environment in the early product design stage. This kind of more aggressive design tendency is referred to as green life-cycle engineering design (Otto & Wood, 2001; Tseng & Chen, 2004).

The so-called product life cycle refers to the total amount of time from material, manufacturing, assembly, consumer use, and final disposal or recycle of a product, and green life cycle is mainly determined by the last two stages, product use, disposal or recycle. While the use of a product will affect its life span, the disposal and recycle of a product will definitely affect the environment and the resource availability. To prolong the product's life cycle and to make the most of resources, the end of the product life cycle does not imply the disposal of the components. Instead, we need to solve the problem from the root of the enterprise activities, especially from the R&D of new products (Tseng & Chen, 2004). Many researchers have explored the issue from different points of view, such as design for environment (DFE), design for recycling (DFR), and design for disassembly (DFD) (Güngör

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& Gupta, 1999; Lambert, 2003). Due to the fact that well-designed modular structures can improve product life-cycle activities, modularity plays a more important role than the whole product life-cycle approach. For example, not only will common modules increase the chances of efficient reuse and recycling operation, they also feature ease of upgrade and maintenance, ease of product diagnosis, repair, and disposal, and so on.

Taking green life cycle into consideration, the authors attempted to apply the green modular concept to product design. Advantages for this study are listed as follows (Gu & Sosale, 1999; Otto & Wood, 2001; Zhang & Gershenson, 2003):

(1) Reexamination of product functions and specifications ensures that the goal of environmental protection can be achieved.
(2) Reduction in product assembly time can enhance the efficiency of production.
(3) Products or product components can be recycled, reused and disposed of more easily.
(4) The life-cycle cost estimation enables designers to bring product cost into control.

There are different perspectives with respect to measuring the product modularity. Jose and Tollenaere (2005) had made a comprehensive review regarding the modular design issue. In Section 2, the different viewpoints will be discussed. In the past, most conceptual descriptions have been rendered regarding the green-oriented modular study but a scientific methodology is rarely seen. In our study, a new methodology of green-oriented modular design will be proposed in Section 3. The approach comprises the following three parts:

(1) Clarifying the liaison intensity of components: in addition to clarifying the liaison relationships of components through visualized diagrams, the liaison intensity of components is decided by their engineering attributes.
(2) The clustering algorithm: the goal of clustering is to assign the components whose liaison intensities are stronger in the same module. In this way, the liaison intensities among different modules are relatively weaker, indicating that it is easy to connect the components if they are assigned to the same module.
(3) Green pollution and cost analysis: while changing the design specification, designers need to green pollution take and costs into consideration so that they can work out the proper design ideas in accordance with the material property to fulfill the product functions.

These three parts will be discussed in Sections 4–6 respectively. In Section 7, the design of a table lamp will be used to illustrate the methodology proposed in this study. Finally, conclusions are made in Section 8.

## 2. Background of product modularity

### 2.1. Diverse viewpoints

In the descriptive model of product functions, according to Otto and Wood (2001), modules can be defined as the integral physical structures corresponding to specific product functions. Meanwhile, the product function model is closely related to the customer's needs. Therefore, a proper modular design is able to reduce the production cost and assemble components effectively into new products to cope with the rapid change of customer's needs. The approach to meeting the customer's needs and function specifications is called the function-based modular design. In the past, different methods had been proposed to explore the function-based modular design issue; for example, Huang and Kusiak (1998) and Kreng and Lee (2004).

In the assembly-based modular design method, products are generally described by liaison graph proposed by De Fazio and Whitney (1987). Researchers need to deal with modules on the basis of network partition and analysis the subassemblies or modules from the stability viewpoint. Lee (1994) and Tseng, Chang, and Yang (2004) are typical representation for this approach of assembly-based modular design.

In general, the manufacturing-based idea does not cover the algorithm for the formation of product modules. Emphasis is often placed upon smooth connections between the design and manufacturing phases. In this domain, He and Kusiak (1996) and Kahoo and Situmdrang (2003) used manufacturing time as the criteria for efficiency evaluation.

On the other hand, the traditional low-cost and mass production model has difficulty in meeting the requirements of the contemporary era. Mass customization aims to provide customer satisfaction with increasing variety and customization without a corresponding increase in cost and lead time. Enterprises have to cope with the frequent variation of product specifications by a stock strategy of bigger numbers of components and modules in the customized environment. Therefore, the exploration of modular design will help with the production and control of mass customization. In terms of mass customization, Mikkola and Gassmann (2003) and Fujita and Yosshida (2004) offered a valuable evaluation method for this issue.

According to the green life-cycle-based concept, modular design is focused upon the environmental level. Newcomb, Bras, and Rosen (1998) used group techniques to develop modular design; Gu and Sosale (1999) used the simulated annealing algorithms to explore modular design; Qian and Zhang (2003) proposed an environmental analysis model for achieving the modular goal.

### 2.2. Problem formulation

As mentioned earlier, the paper attempts to focus on the green life cycle of product design. Three different problems should be taken into consideration in green modular design: (1) the descriptive way of product models and the calculation of liaison intensity of components, (2) the clustering method, and (3) the evaluation of the clustering result. Therefore, a new approach is proposed in this paper.

In this study, the liaison graph proposed by De Fazio and Whitney (1987) is employed to describe products. In such graphic models, the relationships between components are clearly presented. Fig. 1 shows an example of the liaison graph in which nodes represent components and arcs represent the liaison intensity between components. Fig. 1a demonstrates the graphic model for a pen and Fig. 1b shows the pen's liaison graph. In the diagram, the Ink–Tube denotes that there is a contact relationship between components and a new idea about the liaison intensity is decided by the engineering attributes of components, which is defined as the component liaison intensity (LI) in this study. A higher LI indicates a more difficult type of combination and a smaller LI means a simpler type of combination.

Secondly, in terms of the clustering methodology, Gu, Hashemian, and Sosale (1997) adopted traditional genetic algorithms (GAs) but the number of modules and the content size should be set previously, which is an evident disadvantage. To deal with such problems, Falkenaur (1998) once proposed using GGAs to solve the clustering problem. In Falkenauer's view, traditional GAs have three limitations regarding clustering problems: (1) the traditional type of encoding wastes redundant space; (2) it is not easy to generate good-quality offspring population through the standard reproduction mechanism such as Roulette wheel; and (3) the standard exchange mechanisms like crossover and mutation tend to spoil the quality of the offspring population.

Thirdly, the authors employed the green pollution index and cost viewpoint to evaluate the clustering output. The results obtained from the pollution and cost analyses can help designers select suitable ideas according to the material property as well as the specific requirements of product functions.

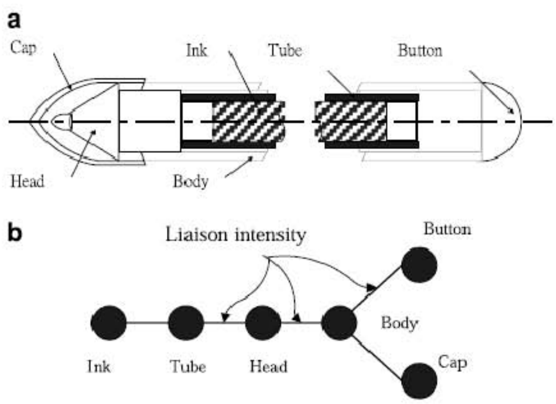


Fig. 1. Liaison graph of a pen.

## 3. Outline framework and related assumption for green-oriented modular design

The proposed methodology for the green modular design is shown in Fig. 2. The detail procedure is illustrated as follows:

Stage 1: Build up the scoring system:
- Step 1: Evaluate the liaison intensity of product (Section 4.2).
- Step 2: Calculate the liaison intensity (Section 4.3).

Stage 2: Grouping genetic algorithms:
- Step 3: Use the heuristic algorithm as the initial population (Section 5.3).
- Step 4: Reproduction, an optimal rate between 0 and 1 is randomly generated for the use of reproduction. Such a rate serves as the threshold for the selection of chromosome.
- Step 5: Crossover (Section 5.4).
- Step 6: Mutation (Section 5.5).
- Step7: Calculate the fitness value (Section 5.2).

Stage 3: Green material analysis:
- Step 8: Determine the green polluted percentage.
- Step 9: Evaluate the pollution value of each component (Section 6.1).
- Step 10: Product redesign (Section 6.3).
- Step 10-1: Choose alternative material of low pollution and cost (Section 6.2).
- Step 10-2: Improve the liaison intensity of the chosen module and its related modules.
- Step 11: Check if the adjusted design is satisfactory. If not, go back to Step 9, change the polluted percentage or change the liaison intensity in Step 1. If yes, end of the green pollution analytic flow.

Some assumptions for the proposed methodology are listed as follows:

(1) In this study, emphasis is placed on the liaison intensity between parts, and green cost information to help with the designer's decision-making. Whether a strategy is correct depends upon the total product design. While the product design strategy is not considered in the study, it is assumed that during design alteration stage, the right decision can be made by the designer.
(2) For each engineering attribute, the value of liaison intensity is correct and fully represented the tight degree of connection between components.
(3) During the evaluation of modular design, the product design will be unchanged. That is to say, the total number of components and liaisons are fixed.
(4) For the cost estimation, we assume the material cost of component is sensitive to its weight. When the material is modified, it is hypothesized that the unit

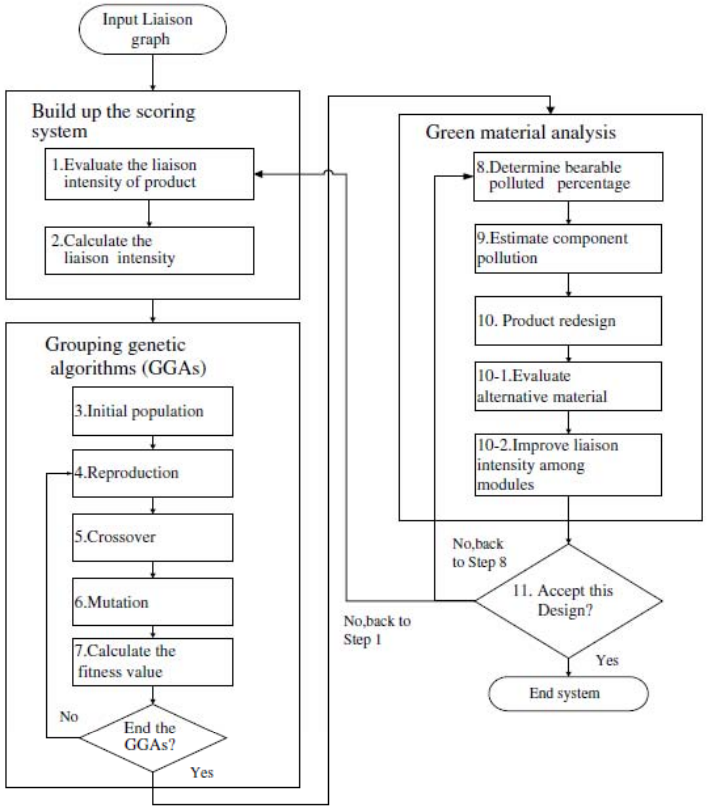


Fig. 2. Proposed flowchart of green modular design process.

material and manufacturing costs are known (Shehab & Abdalla, 2001; Zhang & Gershenson, 2003).

(5) In the assembly and manufacturing cost, the time estimation for assembly and manufacturing is assumed to be known. The assumption is supported by previous research result (Boothroyd, Dewhurst, & Knight, 1994; Zhang & Gershenson, 2003). In practice, the time estimation can be predicted by the methods of time measurement (Tseng & Tang, 2006).

(6) Any component or module produced by methodologies that can be entirely supported by manufacturers and suppliers.

## 4. Estimation of liaison intensity among components

### 4.1. Terminology description

The section explains the definitions proposed to deal with modular design. Suppose an assembly product $P$ is composed of a set of elements called components. These components are connected through mechanical links (liaisons). In this non-oriented connected graph $G(C,L)$, $C$ is the set of $N_c$ nodes representing the components of the product, and $L$ is the set of $N_l$ edges symbolizing the links (liaisons) between these components (De Fazio & Whitney, 1987).

Product $P = \{C_i |\ i = 1, 2, 3, \ldots, N_c\}$
Interconnected by $N_l$ liaisons, then
$L = \{l_{st}|s,\ t = 1, 2, 3, \ldots, N_l,\ l_{st}$ represent the liaison between $C_s$ and $C_t$; $s$ and $t$ represent the component number in Product $P$, $s \neq t\}$

With the definition of a liaison, it is possible to define a module. A module is a subset of $N_m$ components from $P$, so that the liaison subgraph generated from the corresponding $N_m$ vertices is connected. If a product $P$ can be decomposed into $N_k$ modules, such a product can be described as follows:

Product $P = \{M_i | i = 1, 2, 3, \ldots, N_k\}$

### 4.2. Evaluation items

In this study, a number from 0 to 100 is employed to describe the liaison intensity between components. When the number is bigger, the liaison intensity is higher. The liaison intensity is decided by four engineering attributes of components such as the contact type, combination type, tool type, and accessed direction. This kind of evaluation is similar to the product disassembility evaluation method proposed by Das, Yedlarajiah, and Narendra (2000). While the weight for each engineering attribute can be decided by the managerial division according to the company's policy, the weights of these four attributes used in this study are contact type—30%, combination type—20%, tool type—35%, and accessed direction—15%. These four engineering attributes of components are described below. The higher liaison intensity (**LI**) score represents the tighter connection degree between components. The values about LI from Tables 1–4 can be reset depending on the designer's domain knowledge.

#### *4.2.1. Contact type*

The contact type depicts the contact area and contact point between components. The degree of contact between two components is higher if the number of contact points or the contact area is bigger. Five grades of contact (Table 1) are used in this study: point contact, line contact, single face contact, multi-point contact, and multi-face contact, from which the point contact has the weakest liaison, and the multi-face contact has the strongest liaison.

#### *4.2.2. Combination type*

The combination type attribute depends on the tightness of component combination. As shown in Table 2, four types of combination attributes are defined in this study: put on, insert, turn in, deep combine, and not disassemble. Among them, put on is an easy combination type; insert is more difficult than put on; and turn in is the most difficult combination type.

#### *4.2.3. Tool type*

This engineering attribute takes the operation difficulty of tools into consideration. As can be seen in Table 3, five categories are used in this study: hand, screwdriver, small tool, special tool, and large tool. The tool type of which the operation difficulty is bigger indicates that it is more difficult to combine the components.

#### *4.2.4. Accessed direction*

The accessed direction attribute, as the name suggests, considers the intensity of components from the viewpoint of feasible combination directions. A bigger number of accessed angles indicate that the combined components are less interfered by the other components. In this study, $\pm x$, $\pm y$, and $\pm z$ are employed to describe the accessed direction. The number of accessed angles represents the degree of component intensity. As shown in Table 4, five degrees, from strong to weak, 5, 4, 3, 2 and 1, are defined in this study.

Table 1
Intensity of contact type

| Attribute | Liaison intensity | Description |
|---|---|---|
| Point contact | 6 | The contact part is a point |
| Line contact | 12 | The contact part is a line |
| Single face contact | 18 | The contact part is a face |
| Multi-point contact | 24 | Many points will be contacted |
| Multi-face contact | 30 | Many faces will be contacted |

Table 2
Intensity of combination type

| | Attribute | Liaison intensity | Description |
|---|---|---|---|
| Combination type | Put on | 4 | Two components can be combined only by putting one on the other; precise operation is not necessary |
| | Insert | 8 | Precise insertion is needed to combine two components |
| | Turn in | 12 | Two components should be combined with tools and precise turning forces |
| | Deep combine | 16 | Two components should be combined with tools, and a forceful precise operation |
| | Not disassemble | 20 | Two components should be combined with tools and once combined, they will be disassembled only by tearing them down |

Table 3
Intensity of tool type

| Attribute | Liaison intensity | Description |
|---|---|---|
| Hand | 7 | Two components can be combined by hand |
| Screwdriver | 14 | A screwdriver is needed to combine two components |
| Small tool type | 21 | A small tool is needed to combine two components |
| Special tool type | 28 | A special tool is needed to combine two components |
| Large tool type | 35 | A large tool is needed to combine two components |

Table 4
Intensity of accessed direction

| Attribute | Liaison intensity | Description |
|---|---|---|
| 5 Angles | 3 | Two components can be combined from 5 angles |
| 4 Angles | 6 | Two components can be combined from 4 angles |
| 3 Angles | 9 | Two components can be combined from 3 angles |
| 2 Angles | 12 | Two components can be combined from 2 angles |
| 1 Angle | 15 | Two components can be combined from 1 angle |

### 4.3. Computing intensity

With the liaison intensity in the above four engineering attributes, the total component liaison intensity (LI) between components can be denoted as

$$\mathrm{LI}_i = \mathrm{CT}_i + \mathrm{CB}_i + \mathrm{TL}_i + \mathrm{AD}_i \quad (1)$$

where $\mathrm{LI}_i$ represents the total liaison intensity of the $i$th component; $\mathrm{CT}_i$ represents the contact type intensity of the $i$th component; $\mathrm{CB}_i$ represents the combination type intensity of the $i$th component; $\mathrm{TL}_i$ represents the tool type intensity of the $i$th component; $\mathrm{AD}_i$ represents the accessed direction intensity of the $i$th component.

## 5. Grouping genetic algorithm (GGA)

### 5.1. Encoding

The diagram shown in Fig. 3 illustrates the way of coding proposed in this paper, each gene of which stands for a module. Such kind of genetic coding features a flexible length of the chromosome, which is helpful for searching the optimal number of modules. Moreover, it avoids the problem that too long a chromosome will reduce the efficiency. For a chromosome composed of five modules "ABCDE", the number of modules can be expressed as $A=\{1\}$, $B=\{3,6\}$, $C=\{4\}$, $D=\{2\}$, $E=\{5\}$. Each gene can correspond to the relative components. For example, Module B includes Parts 3 and 6.

### 5.2. Fitness design

If $C_l$ and $C_k$ represent two components in a module $M_i$, then the liaison intensity between them can be expressed as $\mathrm{LI}_{lk}$, where $T_i$ stands for the accumulated liaison intensity in module $M_i$. And because the arc in the liaison graph does not have specific directions, the accumulated liaison intensity should be divided by 2, as shown in Formula (2):

$$T_i = \sum_{C_l \in M_i} \sum_{C_k \in M_i} \mathrm{LI}_{lk}/2 \quad (2)$$

Moreover, the accumulated liaison intensity is a constant $\mathrm{LI}_{\mathrm{total}}$, because the total number of liaisons is fixed. The goal of GGA setting is to maximize the liaison intensity within the module ($\mathrm{LI}_{\mathrm{intra}}$) and minimize the liaison intensity between modules ($\mathrm{LI}_{\mathrm{inter}}$). More importantly, a stronger $\mathrm{LI}_{\mathrm{inter}}$ means that the $\mathrm{LI}_{\mathrm{intra}}$ is weaker, indicating that it is easy to assemble and disassemble components in a module. Because the $\mathrm{LI}_{\mathrm{intra}}$and $\mathrm{LI}_{\mathrm{inter}}$ are mutually exclusive, if we subtract the $\mathrm{LI}_{\mathrm{intra}}$ from the total liaison intensity ($\mathrm{LI}_{\mathrm{total}}$), we get the $\mathrm{LI}_{\mathrm{inter}}$ of a module. This is expressed as follows:

$$\mathrm{LI}_{\mathrm{inter}} = \mathrm{LI}_{\mathrm{total}} - \mathrm{LI}_{\mathrm{intra}} \quad (3)$$

And if there are $q$ modules after the clustering task, we need to calculate the sum of the liaison intensity of each module. Therefore, the maximum $\mathrm{LI}_{\mathrm{intra}}$, the biggest liaison intensity in a module, can be denoted as Formula (4):

$$\mathrm{LI}_{\mathrm{intra}} = \sum_{i=1}^{q} T_i \quad (4)$$

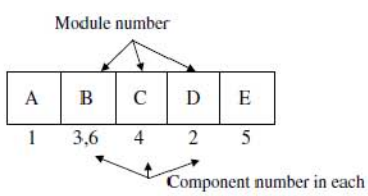


Fig. 3. Encoding for grouping genetic algorithms.

### 5.3. Initial population

In the initial stages of GGA, many chromosome populations should be generated in that the variety of the initial population and better fitness values will effectively improve the evolution efficiency during the searching of the optimal solutions. Ericsson and Erixon (1999) once pointed out a way to look for the ideal number of modules and components (Formula (5)), which is based on the assumption of minimizing the assembly time:

$$\text{Ideal number of modules} \leqslant \sqrt{\text{Component number}} \quad (5)$$

In this study, the upper bound of the number is calculated by Formula (5) and the lower bound of the number of modules is set to be 1. The initial genetic combination of the chromosome is then built up through a random greedy algorithm as listed below:

Step 1: Generate randomly a feasible number of modules under the limit of the maximum number of modules.

Step 2: Assign randomly the first component to any module.

Step 3: In a higher priority, assign the rest of the components to the modules with higher liaison relationships. If there is no proper module to assign, then assign them randomly. Repeat this step until all components are assigned to product modules.

### 5.4. Crossover

In GGA, the crossover operation is not decided by the crossover rate. In a single-point operation, two parent generations will be selected, each crossover point of which is randomly selected. From the crossover point, new offspring generations will be obtained by exchanging the right side of a parent generation and the left side of another parent generation. Repeating this step can generate a new offspring generation. To generate excellent offspring generations, we employ the GGA crossover operation as follows:

Step 1: After a pair of chromosome is chosen, generate randomly two crossover points for each of them to define the exchange range (Fig. 4a).
Step 2: Insert the central site of the second chromosome into the first chromosome (Fig. 4b).
Step 3: Remove the same components and empty modules in the second chromosome and the first chromosome. Pick out the single object left in the module (Fig. 4c and d).
Step 4: Insert the selected single object into the second chromosome.
Step 4-1: Calculate the liaison intensity in the module. New fitness value should be calculated after Steps 1 and 2 (Formula (4)).
Step 4-2: Limits of the maximum number of modules should be checked for the number of modules after the crossover operation. If the outcome does not meet the requirement, insert components or add new modules.
Step 4-3: Calculate the effects the single component may have on the fitness value when it is inserted into every possible module. Assign the rest of the components to other possible modules. If possible modules are not found, then add new modules and assign these components to them.
Step 5: Repeat Steps 2–4 for the first chromosome.

In the above procedure, Step 4 is different from that in the original GGA algorithms (De Lit, Falkenauer, & Delchambre, 2000). There are two principles in the GGA crossover procedure.

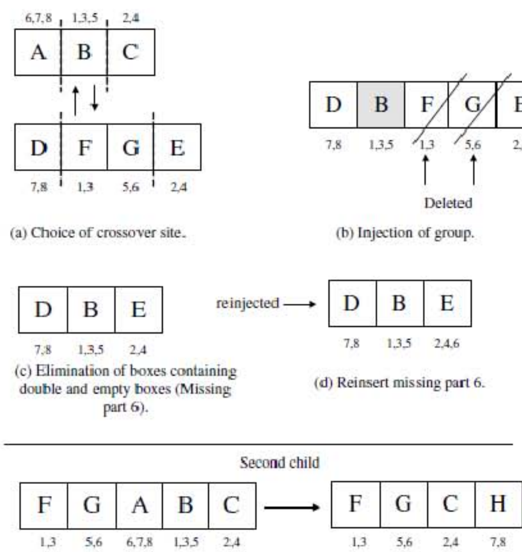


Fig. 4. Crossover for grouping genetic algorithms.

*Principles for inserting components*: According to the fitness values obtained from Step 4-3, find the optimal insert operation. If the improvement is not evident, insert randomly components into any module.

*Principles for adding new modules*: Assign the rest of the components into possible modules according to the liaison intensity between components. If no suitable modules are found, assign them randomly to the newly added modules.

### 5.5. Mutation

De Lit et al. (2000) suggested three strategic considerations in the GGA application: create a new group, delete an existing group, and move the components randomly in a group. If no feasible chromosomes are found, then the heuristic solution can help correct such irrationality. The mutation operation will be executed only when the chromosome's mutation probability is equal to or smaller than a certain value. This kind of mechanism can prevent us from falling in the local optimal value and avoid the early convergence problem.

## 6. Balance between cost and green design

### 6.1. Green analysis

The green analysis is conducted in this study according to the pollution value offered by Eco-indicator99 (http://www.pre.nl/). The Eco-indicator refers to the pollution reference value the component material causes to the environment. The higher value means higher injuries for the environment after the product is used. Because weight is used as an investigation unit for Eco-indicator, the estimated pollution value for a component can be represented as Formula (6):

$$\text{Poll} = \text{Weight} \times \text{Indicator} \quad (6)$$

In Formula (6), Poll indicates the pollution value of a component. The value can be regarded as dimensionless figures. For the Eco-indicator point (Pt), 1Pt is representative for one thousandth of the yearly environmental load of one average European inhabitant. Weight denotes the weight of the component (kg); and Indicator represents the unit pollution index of a component.

### 6.2. Cost analysis

In the perspective of product design estimation, the total cost can be determined by three major cost viewpoints: (1) material cost, (2) manufacturing cost, and (3) assembly cost. Therefore, the total cost can be estimated by Formula (7):

$$\text{TC} = C_{\text{m}} + C_{\text{mpc}} + C_{\text{a}} \quad (7)$$

where TC represents the total cost (NT$). In the year of 2006, 1 US dollar is approximately equal to NT$32.8 and

0.78 Euros. $C_m$ is the cost of material, $C_{mpc}$ is the cost of manufacturing, $C_a$ is the cost of assembly.

The material cost $C_m$ can be defined by Formula (8):

$$C_m = C_{mu} \times W_m \tag{8}$$

where $C_{mu}$ indicates the unit cost of material (NT$/kg); and $W_m$ indicates the material weight (kg).

The manufacturing cost $C_{mpc}$ can be computed based on the feature methodology developed by Shehab and Abdalla (2001). In their methodology, a feature is defined as a generic shape carrying product information from computer-aided design, or communication between manufacturing and design. The manufacturing cost $C_{mpc}$ can be decided by Formula (9):

$$C_{mpc} = C_{pcu} \times T_{pcu} \tag{9}$$

where $C_{pcu}$ means the unit cost of manufacturing (NT$/s); $T_{pcu}$ indicates the time for manufacturing (s).

The assembly cost $C_a$ can be decided by Formula (10):

$$C_a = C_{au} \times T_{au} \tag{10}$$

where $C_{au}$ represents the unit assembly cost (NT$/s), and $T_{au}$ refers to the assembly time (s).

### *6.3. Design modification and the modular component analysis*

In the study, designers can change the design principles according to change of component materials so as to reduce the component liaison intensity between modules. Such design principles are combined into the following five rules:

1. Redesign the product component according to the outcome pollution value or cost evaluation.
2. For the change of material, designers need to evaluate the liaison intensity of the newly added component.
3. When the material is changed, designers need to take into consideration the liaison intensity of the related combined components.
4. When the material is changed, designers need to delete some liaison intensity of the related components.
5. The engineering attributes between modules, including contact type, combination type, tool type, and accessed direction are suggested to change.

With the green pollution value and cost data at hand, designers can choose alternate materials to reduce the pollution value in a module. Furthermore, the intra liaison intensity between modules can be adjusted according to practical needs.

## 7. A practical example

As shown in Fig. 5a, the table lamp is composed of 22 components and 22 liaisons. First of all, we need to evaluate the liaison intensity of each component in terms of each engineering attribute. The outcome liaison intensity is shown in Table 5. Take liaison 1–2 as an example, it shows the relationship between Components 1 and 2; the single face contact has an intensity of 18 (Table 1); the put on combination type's intensity is 4 (Table 2); the intensity of the hand type of assembly is 7 (Table 3); and the intensity of the accessed direction is 3 for five angles (Table 4). According to Formula (1), the total component liaison intensity $LI_{12} = 18 + 4 + 7 + 3 = 32$. Table 5 serves as input data for the GGA.

In this study, we used Borland C++6.0 to compile the program and the test environment was on a Pentium 2.8 GMHz PC at 512 MB RAM. The operation interface for LI estimation is shown in Fig. 6. In this case, the population number is set at 20; the number of evaluation generations, 100; the mutation rate, 0.1; and crossover rate, 0.8. According to Formula (5), we need to pinpoint the upper bound of the number of components in each module. Therefore, the maximum number of modules is set to be 5 ($\sqrt{\text{Component number}} = \sqrt{22} \cong 4.69$).

When the fitness value reaches 813, an optimal situation can be obtained from the GGAs. The results are {6, 19, 3, 20}{9, 10, 8, 7}{4, 1, 2, 22, 21}{15, 5, 18, 16, 17}{13, 14, 11, 12}, each of which represents a specific module of the table lamp. Each number represents specific components that are shown in Fig. 5b. Then, according to the Eco-indicator99 (Formula (6)), the component material pollution analysis is conducted to check the pollution percentage (Table 6). In Table 6, the total pollution value can be got from the summation for the Poll value. The total pollution value is 183.4 for the lamp example. Then we can calculate the last column percentage (%). For example, the percentage of Component 1 can be worked out as 26.4/183.4 = 14.39%. In this study, two redesign cases are further discussed.

### *7.1. Situation 1: If the current bearable green pollution value is 20%*

Because Steps 1–7 have been discussed earlier and are the same for the two situations, only the algorithms after Step 8 are presented here.

Step 8: Component 8's pollution value is the highest (Table 6). Obviously, Component 8 (Soft_pipe) should be improved.

Step 9: In terms of the individual component pollution evaluation, Component 8's specifications are weights = 0.2 kg; pollution unit value = 240; environmental pollution index = 48; and green polluted percentage = 26.17%. The material for Component 8 should be adjusted.

Step 10: The major function of Component 8 is to support the lamp. The pollution value for the material before design modification is 240

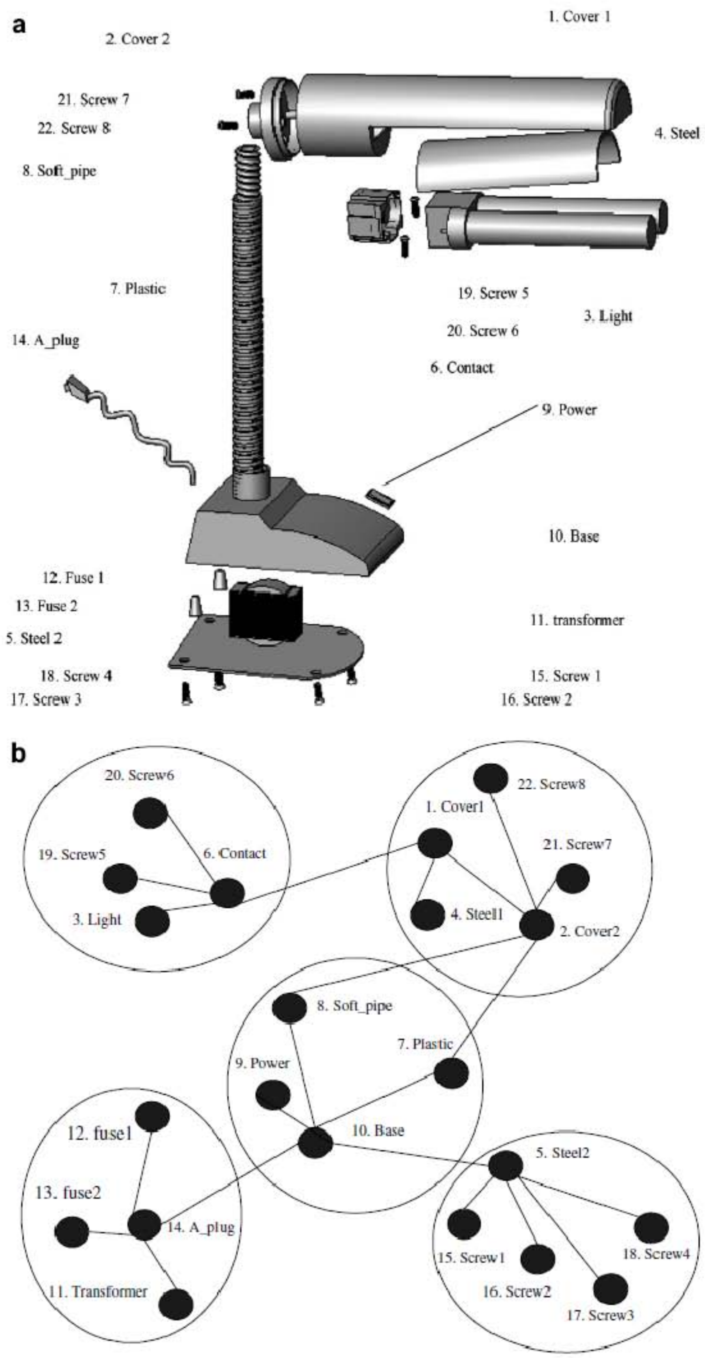


Fig. 5. Case study—table lamp. (a) Part diagram and (b) liaison graph.

(Cast iron). It is suggested to use the Electro Steel because of its lower pollution value of 24.

Step 10-1: The material and manufacturing costs will be changed when the material is changed. The material and manufacturing cost before and

Table 5
Estimate liaison intensity for table lamp

| Liaison | Contact type | Combination type | Tool type | Accessed direction | Liaison intensity |
|---|---|---|---|---|---|
| 1–2 | SFC | Put on | Hand | 5 Angles | 32 |
| 1–4 | SFC | Insert | Hand | 1 Angle | 48 |
| 1–6 | SFC | Put on | Hand | 5 Angles | 32 |
| 2–7 | LC | Put on | Hand | 5 Angles | 26 |
| 2–8 | LC | Insert | Hand | 5 Angles | 30 |
| 2–21 | PC | Turn on | Small tool type | 1 Angle | 54 |
| 2–22 | PC | Turn on | Small tool type | 1 Angle | 54 |
| 3–6 | MFC | Insert | Hand | 1 Angle | 60 |
| 5–10 | SFC | Put on | Hand | 5 Angles | 32 |
| 5–15 | PC | Turn on | Small tool type | 1 Angle | 54 |
| 5–16 | PC | Turn on | Small tool type | 1 Angle | 54 |
| 5–17 | PC | Turn on | Small tool type | 1 Angle | 54 |
| 5–18 | PC | Turn on | Small tool type | 1 Angle | 54 |
| 6–19 | PC | Turn on | Small tool type | 1 Angle | 54 |
| 6–20 | PC | Turn on | Small tool type | 1 Angle | 54 |
| 7–10 | LC | Put on | Hand | 5 Angles | 26 |
| 8–10 | LC | Insert | Hand | 5 Angles | 30 |
| 9–10 | MPC | Insert | Hand | 4 Angles | 45 |
| 10–14 | PC | Insert | Hand | 1 Angle | 36 |
| 11–14 | PC | Put on | Small tool type | 1 Angle | 60 |
| 12–14 | PC | Turn on | Hand | 1 Angle | 40 |
| 13–14 | PC | Turn on | Hand | 1 Angle | 40 |

PC: point contact; LC: line contact; SFC: single face contact; MPC: multi-point contact; MFC: multi-face contact.

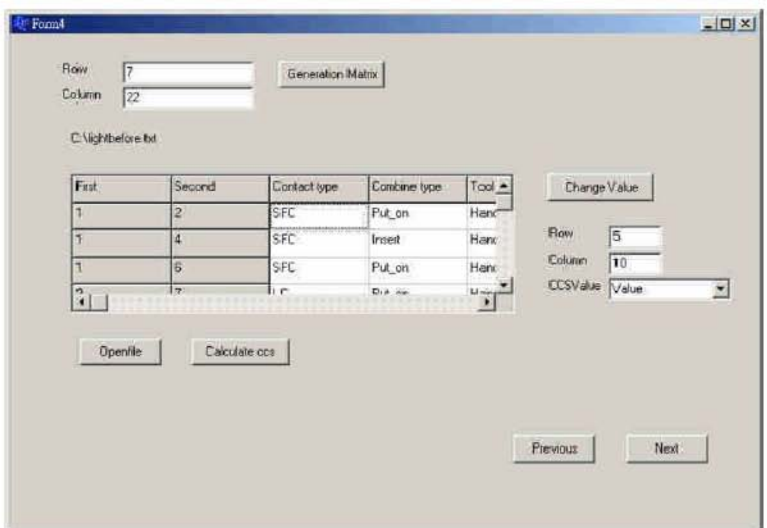


Fig. 6. Interface for liaison intensity estimation.

after modification for Component 8 is shown in Table 7.

Step 10-2: Because Component 8 is a single component, the assembly engineering attribute remains the same. Therefore, the assembly cost stays unchanged.

Step 11: Check whether the design modification is satisfactory. Through green pollution value analysis, it is found that the pollution value is much lower, dropping from 48 to 4.8, and that the cost is estimated to rise from NT$5.32 to NT$5.7.

Table 6
Pollution percentage analysis

| Component | Name | Weight | Material | Indicator | Poll | % |
|---|---|---|---|---|---|---|
| 1 | Cover1 | 0.08 | Plastic | 330 | 26.4 | 14.39 |
| 2 | Cover2 | 0.03 | Plastic | 330 | 9.9 | 5.4 |
| 3 | Bulb | 0.04 | Glass | 51 | 2.04 | 1.11** |
| 4 | Steel1 | 0.01 | Steel | 86 | 0.86 | 0.47 |
| 5 | Steel2 | 0.1 | Steel | 86 | 8.6 | 4.69 |
| 6 | Contact | 0.05 | Plastic | 330 | 16.5 | 9** |
| 7 | Plastic | 0.01 | Plastic | 330 | 3.3 | 1.8 |
| 8 | Soft_pipe | 0.20 | Cast iron | 240 | 48 | 26.17* |
| 9 | Power | 0.01 | Plastic | 330 | 3.3 | 1.8 |
| 10 | Base | 0.04 | Plastic | 330 | 13.2 | 7.2 |
| 11 | Transformer | 0.30 | Steel | 86 | 25.8 | 14.07 |
| 12 | Fuse1 | 0.01 | Plastic | 330 | 3.3 | 1.8 |
| 13 | Fuse2 | 0.01 | Plastic | 330 | 3.3 | 1.8 |
| 14 | A_plug | 0.05 | Plastic | 330 | 16.5 | 9 |
| 15 | Screw1 | 0.00125 | Cast iron | 240 | 0.3 | 0.16 |
| 16 | Screw2 | 0.00125 | Cast iron | 240 | 0.3 | 0.16 |
| 17 | Screw3 | 0.00125 | Cast iron | 240 | 0.3 | 0.16 |
| 18 | Screw4 | 0.00125 | Cast iron | 240 | 0.3 | 0.16 |
| 19 | Screw5 | 0.00125 | Cast iron | 240 | 0.3 | 0.16** |
| 20 | Screw6 | 0.00125 | Cast iron | 240 | 0.3 | 0.16** |
| 21 | Screw7 | 0.00125 | Cast iron | 240 | 0.3 | 0.16 |
| 22 | Screw8 | 0.00125 | Cast iron | 240 | 0.3 | 0.16 |

*Notes*: The mark "*" indicates the components chosen from 20% bearable polluted percentage, and the mark "**" indicates those chosen from the whole modular concept.

Table 7
Material cost and manufacturing cost change of Component 8

| | Before modification | | | After modification | | |
|---|---|---|---|---|---|---|
| | Unit | Weight | Cost | Unit | Weight | Cost |
| Material cost | $C_{mu}$ 2.8 | $W_m$ 0.2 | $C_m$ 0.56 | $C_{mu}$ 3.0 | $W_m$ 0.2 | $C_m$ 0.6 |
| Manufacturing cost | $C_{pcu}$ 4.76 | $T_{pcu}$ 1.0 | $C_{mpc}$ 4.76 | $C_{pcu}$ 5.1 | $T_{pcu}$ 1.0 | $C_{mpc}$ 5.1 |

Table 8
Material evaluation for light bulb module

| Component | Before modification | | After modification | |
|---|---|---|---|---|
| | Material | Indicator | Material | Indicator |
| 3 | Glass (green) | 51 | Glass (brown) | 50 |
| 6 | Plastic | 330 | PVC | 240 |
| 19 | Cast iron | 240 | Electro Steel | 24 |
| 20 | Cast iron | 240 | Electro Steel | 24 |

### 7.2. Situation 2: Designer can replace the whole module according to the bearable green pollution value

In the case of table lamp, light bulb module needs to be improved because it is a consumptive component. Therefore, its pollution value should be considered to improve the total module.

Step 8: Analyze the bearable green pollution percentage.
Step 9: The related components for the light bulb module contain Components 3, 6, 19, and 20. Their pollution values are also shown in Table 6.
Step 10: Major components for the light bulb module are Component 3. Components 19 and 20 connect Components 3, 6 and 1. Because the result of clustering indicates that these four components are of the same module, their pollution values are further analyzed and shown in Table 8.

Table 9
Material cost and manufacturing cost change of light bulb module

| Component | Before modification | | | After modification | | |
|---|---|---|---|---|---|---|
| | $C_{mu}$ | $W_m$ | $C_m$ | $C_{mu}$ | $W_m$ | $C_m$ |
| *Material cost* | | | | | | |
| 3 | 2.5 | 0.04 | 0.1000 | 2.6 | 0.04 | 0.1040 |
| 6 | 1.2 | 0.05 | 0.5000 | 1.3 | 0.05 | 0.5500 |
| 19 | 2.8 | 0.00125 | 0.0035 | 3.0 | 0.00125 | 0.0038 |
| 20 | 2.8 | 0.00125 | 0.0035 | 3.0 | 0.00125 | 0.0038 |
| Total cost | | | 0.607 | | | 0.6616 |
| | $C_{pcu}$ | $T_{pcu}$ | $C_{mpc}$ | $C_{pcu}$ | $T_{pcu}$ | $C_{mpc}$ |
| *Manufacturing cost* | | | | | | |
| 3 | 3.25 | 1.0 | 3.2500 | 6.24 | 1.0 | 6.24 |
| 6 | 1.8 | 1.0 | 1.8000 | 1.95 | 1.3 | 2.54 |
| 19 | 4.76 | 0.001 | 0.0048 | Combine | Combine | 0 |
| 20 | 4.76 | 0.001 | 0.0048 | Combine | Combine | 0 |
| Total cost | | | 5.0596 | | | 8.78 |

Step 10-1: A proper decision should be made if the lower pollution material chosen causes the cost to rise. Consequently, the material and manufacturing costs for a module will be changed. The material cost and manufacturing cost of the light bulb module before and after modification are shown in Table 9.

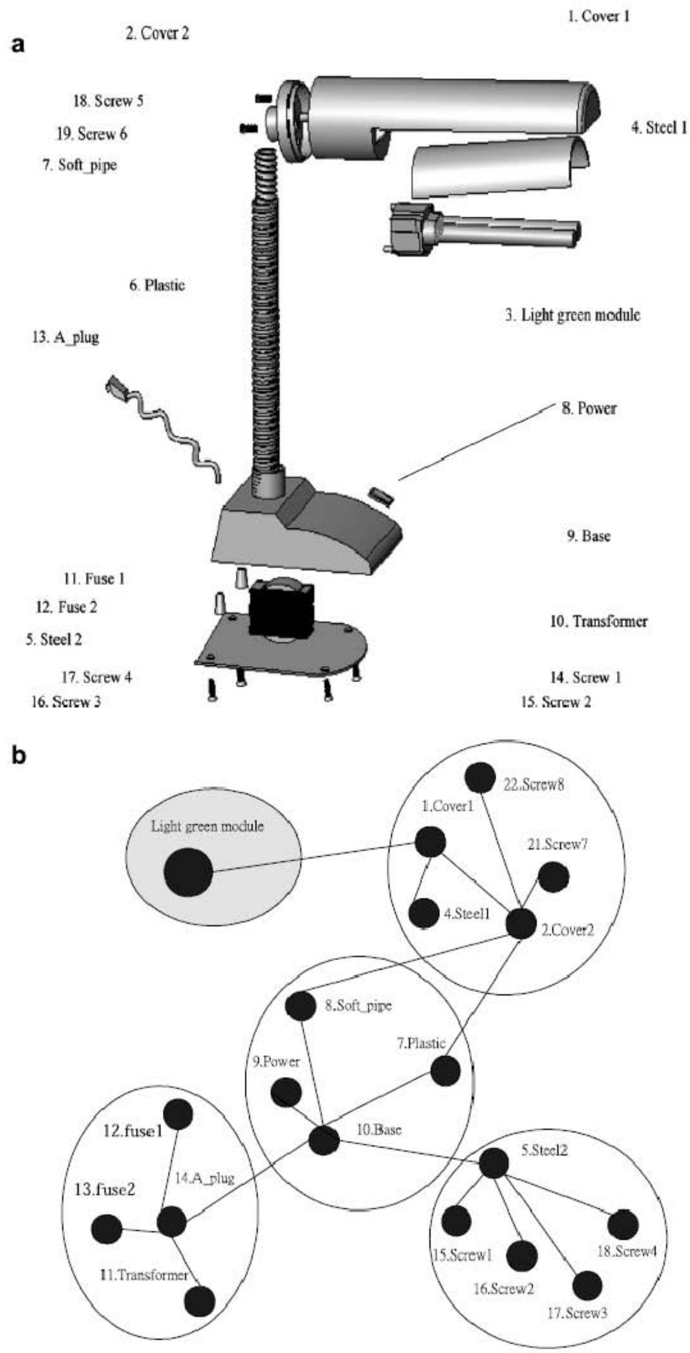


Fig. 7. (a) Revised design for Situation 2 and (b) a revised modular graph for the table lamp.

Table 10
Assembly cost change for light bulb module

| Before modification | | | After modification | | |
|---|---|---|---|---|---|
| Unit | Time | Cost | Unit | Time | Cost |
| $C_{au}$ | $T_{au}$ | $C_a$ | $C_{au}$ | $T_{au}$ | $C_a$ |
| 0.049 | 0.5755 | 0.0282 | 0.049 | 4.2086 | 0.1974 |

Step 10-2: In the case of the light bulb, the liaison intensity between modules is suggested to adopt "easy assembly design." It is suggested that the related modules of the light bulb should be integrated to form a new component so as to enhance the convenience in renewing the component. The modified design for Situation 2 is shown in Fig. 7a, and the improved liaison graph is shown in Fig. 7b. We can find that the light bulb modular is an integral design. The new attributes for liaison intensity are "point contact", "insert" combined type, "hand" tool type and "1 angle" assessed direction type. Moreover, the change in assembly cost is listed in Table 10.

Step 11: Check if the outcome satisfies the designer's goal of design modification. Through the green polluted analysis, the pollution value is changed from 19.14 to 14.06, and the total cost will rise from NT$5.69 to NT$9.64.

Two alterative solutions have been generated in Situations 1 and 2. It is also found that the reduction in pollution value brings forth a rise in the cost and that the liaison intensity between components will change with the design modification. Therefore, the final solution will be decided by the R&D division.

The solution to the environmental pollution problem lies in the root of enterprise activities, the product design. It goes without saying that a subtly built environmental standard and complete database will help set up a better modular design. This will also enable designers to find a choice from the balance between conflicts of cost and green consideration. More importantly, enterprises should follow the management standards as ISO9001, ISO14001 and add the concept of green life cycle to their operation of total supply chain (Ammenberg & Sundin, 2005).

## 8. Conclusions

In this study, new methodologies for evaluating product modularity from the viewpoint of green life cycle are proposed. First, a score system using the liaison graph was adopted to evaluate the liaison intensity between components. Moreover, a GGA was adopted for the clustering of modules. Finally, green pollution and cost analysis was conducted to evaluate the clustering result. When the material of components is changed, the product component design is also modified, and so are the relations of liaison intensity between components. Through a cyclic adjustment procedure of the liaison intensity between components and the design modification, the green modular design can be achieved.

According to the green-oriented product design, it may be the case that the new design will bring forth higher costs. But it is the enterprise's obligation to pay more attention to the environmental protection. In the future, related laws of the environmental protection policy will be drawn up and put into action to regularize the enterprise activities. In addition, enterprises should take responsibility for the increasingly serious environmental pollution problem. The concept of green life cycle should be added in the total supply chain.

It is evident that green-oriented modular design is just a general issue. In the future, focus can be put on the integration of modular design method and other related product development approaches so as to multiple the suggestions of product design. Besides, the green pollution standard and information database should also be established as references for designers. In addition, proper decision-making strategies can be added to help evaluate the liaison intensity between components, making the algorithm more objective and flexible.

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6. Artículo: Nuevos retos en el desarrollo e implementación de un programa de estudio para la siguiente generación de ingenieros de manufactura y/o diseño. Desarrollado por: I. S. Jawahir, K. E. Rouch, O. W. Dillon, Jr., L. Holloway, and A. Hall.

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# Design for Sustainability (DFS): New Challenges in Developing and Implementing a Curriculum for Next Generation Design and Manufacturing Engineers*

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*Trends in innovative product design and manufacture require a paradigm shift in traditional methodologies because they are becoming increasingly ineffective for applications built for sustainable futures. The well-known concept of sustainable development, which is based on sustained growth for environmental, economic and societal benefits, is brought into focus for highlighting the significance of product design and manufacture. The technological challenges posed by the need for implementing innovative design and manufacture call for a need for developing and implementing new educational and training programmes for next generation design and manufacturing engineers. We aim at tackling these challenges with a proposed new curriculum at five different levels. Perpetual material flow and multi life-cycle/multi-use self-healing materials, innovative product and process design and development are in the core of the proposed design for sustainability educational programmes.*

**Keywords:** product design; manufacturing; sustainability; education; curriculum

## INTRODUCTION

RECENT TRENDS AND ADVANCES in product design and manufacture have placed a strong emphasis on developing advanced curricula to provide engineers of the future with the basic theories and applications of product manufacturing involving product life-cycle engineering and sustainability principles for societal, economic and environmental benefits. Traditional design for manufacturing educational programmes have long depended on curricula based on concurrent engineering methodologies covering product and process designs, functional design development, concept selection for product design, materials and process selection, process planning including assembly analysis, etc., all aimed at the best design and manufacturing practices for products and economic manufacturing. Growing environmental concerns associated with product life-cycle issues have in recent times inevitably forced the need for new topics in curriculum development largely to cater for societal needs. This has resulted in many universities and colleges developing new courses in product life-cycle engineering and environmentally conscious product design and manufacture at undergraduate and graduate levels. While significant progress is being made in new curriculum development, a lot more needs to be done particularly in the broader sustainability perspective. This would require full understanding of the total life-cycle effects involving innovative methods for products and processes in manufacturing.

From the global and societal viewpoint, it is necessary to see the specific application of the well-known sustainability definition in product design and manufacture. The World Commission on Environment and Development (also known as the Brundtland Commission) defines Sustainable Development as 'the capacity to meet the needs of the present without compromising the ability of future generations to meet their own needs' [1]. In only 12 years from 1987 to 1999 the world's population increased by 20 per cent, from five to six billion. Current projections predict the population reaching around 9.1 billion people by 2050, nearly 150 per cent of today's 6.3 billion [2]. Everything else being equal, meeting even the most basic needs of such a global population will require significant material resources and energy. With their continual depletion, the need for effective and economic use of renewable energy sources and reusable materials becomes significant for economic, environmental sustainability to provide for the world's growing needs. Within this context,

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current educational programmes require major revisions to accommodate scientific principles and applications of sustainability engineering to meet future challenges. Engineers and product and process designers of tomorrow will be expected to demonstrate their knowledge and training in product and process sustainability. A paradigm shift is called for such educational challenges. This will cover the development and application of broader sustainability principles in product design for manufacture encompassing the wider applications of Design for Sustainability (DFS) to allow all related Design for X elements [3]. Recent studies presenting the blueprints and roadmaps for engineering education emphasize new curriculum and course development for education and training of the future workforce in innovative design and manufacturing [4–6].

A historical perspective of sustainability engineering educational programme development is well presented in a recent paper [7] covering the early programmes in the 1990s at the Technical University of Denmark, ETH, Zurich, University of Technology, Netherlands, University of Stuttgart, etc. A growing number of national and international educational institutions are currently embarking on new curriculum development for life-cycle and environmental engineering educational programmes, most notably the initiatives at the Queen's University [7], Michigan Technological University [8], Georgia Tech [9], University of Rhode Island [10], Texas Tech [11], University of Missouri—Rolla [12], University of Technology, Australia [13] and Auckland University, New Zealand [14] are making significant progress. More recent efforts include the sustainable development educational programme at the Engineering Department in Cambridge University [15–16], green design educational program at Carnegie Mellon [17] and the project-based sustainable design programme at MIT [18]. A notably increasing number of colleges and universities are currently initiating programmes on sustainability. The American Society for Engineering Education (ASEE) urges the need for integrating sustainability studies in the traditional engineering curriculum [19] along with the declaration made by 11 global educational organizations, including UNESCO, UNU, IAU, ICS, WFEO, for greening the school curriculum [20]. Also, the joint conference on engineering education and training for sustainable development organized by WFEO, UNEP, WBSD and ENPC (France) provides a solid structure for implementing sustainability educational programmes at undergraduate and graduate levels in universities [21].

New educational challenges are associated with the development of design for sustainability principles and their applications in product design and manufacture. Below we outline these new challenges posed in the traditional evaluation of product life-cycle principles, and the sustainability evaluation methods for products and processes. We shall propose a new curriculum for sustainability engineering with five levels for implementation and describe recent experience in developing a sustainability programme at the University of Kentucky.

## NEW CHALLENGES FOR EDUCATION IN PRODUCT DESIGN AND MANUFACTURING

Traditional product design and manufacturing methods are based on a range of product characteristics such as functionality, performance, cost, time-to-market, etc. Product design and manufacture in this century will require a greater integration of life-cycle, sustainable product/process designs and their implementation in the manufacture of engineered products. This will apply to both consumer products in high volumes and small varieties and highly customized products in low volumes and large varieties. In particular, the design and manufacturing practices for next-generation products need to undergo major changes to include concerns that span the entirety of the traditional life-cycle, and ultimately from the perspective of multiple life-cycles/multi-uses involving perpetual material flow. Novel design methodologies, innovative manufacturing techniques, and effective tools must be developed to address simultaneously total life-cycle issues including:

(a) Reduction of manufacturing costs;
(b) Reduction of product development time;
(c) Reduction of material use;
(d) Reduction of energy consumption;
(e) Reduction of industrial wastes;
(f) Repair, reuse, recovery and recycling of used products/materials;
(g) Environmental and societal concerns.

This paradigm shift in product design and manufacture obviously requires optimized methodologies incorporating environmentally conscious, energy-efficient, lean manufacturing methods with product maintenance, disassembly, material recovery, reuse, remanufacturing and recycling considerations. It promotes a systems thinking in the design of new products and processes and calls for attention to the interests of all stakeholders in our living environment. It requires the devising of new design methodologies, manufacturing processes, post-use processes and enterprise resource planning in order to achieve simultaneously the multiple objectives of improving a company's profitability, bringing new products to market rapidly, conserving natural resources, with environmental concerns.

The new challenges posed by this natural transformation of societal need call for a comprehensive overhaul of the current educational programmes to accommodate courses that provide the scientific principles and applications of the entire life-cycle of manufactured products including multi-use and multi-life materials with perpetual material flow, new materials and process technologies for sustainable designs, and manufacturing processes and systems for sustainability. This requires careful planning and a systematic development of new curricula for implementation at all levels, beginning from high schools through to undergraduate and graduate programmes.

*Product life-cycle concepts*

With the rapid growth in industrialization, the environmental concerns of society reflecting the need for 'design for environment', are often associated with the use of materials and energy, and this has so far led to a significant number of social reforms and regulations by local, state and federal authorities, all aimed at improving societal wellbeing, health, safety, economy and environmental protection. Generally targeted activities include: global climate changes, loss of biodiversity, ozone depletion and toxic emissions, availability of water and its quality, resource depletion, sub-optimal land use, acid deposition, smog, oil spills, effects of radiations, odour, thermal pollutions and landfill exhaustion [22]. The role of disassembly in life-cycle assessment was heavily emphasized in a CIRP keynote paper [23]. Design for sustainability elements and their correlation with evolving life-cycle issues were shown by Tipnis in 1993 [24]. Subsequently, environmental concerns were associated with product disassembly [25], and this was followed by material separation and design for bulk recycling analysis [26–28]. A design for environment software was developed in 1999 [29]. A series of ISO standards have been developed to disseminate and implement the basic principles of life-cycle assessment and management, and these standards provide the framework, goals, and scope, impact assessment methods, etc. [30–33].

The traditional product life-cycle methods have long depended on evaluating the life-cycle in confined five stages: (a) Resource extraction (b) Manufacturing operation (c) Packaging and Shipping (d) Customer use (e) Obsolescence. Designing products with improvements in each of these stages would enhance the life-cycle value of products. While each product is expected to satisfy the designed functionality along with provisions for manufacturability, assembly requirements, reliability, safety, serviceability, environmental compliance, etc., the end-of-life options are generally not well thought out. The economic and environmental analyses performed on products impacting the society are almost entirely developed for a single life-cycle of the product. The material recovery aspect along with possible reuse/multi-use opportunities associated with economic gains and societal and environmental benefits are hardly evaluated. Indeed, the perpetual material flow across multiple life-cycles and multi-use benefits are not considered in traditional practices in the current manufacturing units. The last stage of the above traditional life-cycle analysis, which has been performed by other than the manufacturers, has in recent years increasingly come to be the responsibility of the manufacturers with various lease and take-back options.

Colleges and universities are continuing to become interested in conducting research on product life-cycle issues and on designing manufacturing processes for greater sustainability through sponsored project activities from industry and various funding agencies, but the growth of educational programmes to reflect the current research trends has been very slow. Therefore, a leapfrogging reform in educational programmes would be necessary. Moreover, industry expectation of this new knowledge and skills in sustainability from a fresh graduate joining the workforce is high. Thus, the educational challenges are great for producing adequately qualified and trained engineers, even though meeting these challenges is a mammoth task.

*Assessment of product sustainability*

Almost all previous research deals with product's environmental performance and its associated economic and societal effects largely intuitively, and qualitative descriptions offered are little and are often difficult to measure and quantify. Thus, these analyses mostly remain non-analytical and less scientific in terms of the need for quantitative modelling of product sustainability. The complex nature of the systems property of the term 'product sustainability' seems to have limited the development of a science-base for sustainability. Moreover, the partial treatment and acceptance of the apparent effects of several sustainability-contributing measures in relatively simplistic environmental, economic and societal impact categories has virtually masked the influence of other contributing factors such as product's functionality, manufacturability, reusability with multiple life-cycles, etc. Consideration of a total and comprehensive evaluation of product sustainability can lead to reduced consumer costs over the entire life-cycle of the product, while the initial product cost could be slightly higher in some cases. This benefit is compounded when a multiple life-cycle approach is adopted on the basis of continuous material flow. The overall economic benefits and the technological advances involving greater functionality and sustained quality enhancement are far too great to outscore current practice. The technological and societal impacts are also great for undertaking such an innovative approach.

Current research on product sustainability evaluation shows a consistent trend towards the long-range development of a Product Sustainability Index (PSI) for all manufactured products. This index would be expected to represent the 'level of sustainability' built in a product by taking into account all major contributing sustainability elements and their subelements. Our preliminary work shows the following six product sustainability elements—see Fig. 1 [34]:

1) Product's Environmental Impact;
   - Life-cycle factor (including product's useful life span)
   - Environmental effect (including toxicity, emissions, etc.)
   - Ecological balance and efficiency
   - Regional and global impact (e.g. $CO_2$ emission, ozone depletion, etc.)
2) Product's Societal Impact (Safety, Health, Ethics, etc.);
   - Operational safety
   - Health and wellness effect
   - Ethical responsibility
   - Social impact (including quality of life and peace of mind, etc.)
3) Product's Functionality;
   - Service life/durability
   - Modularity
   - Ease of use
   - Maintainability/serviceability
   - Upgradeability
   - Ergonomics
   - Reliability
   - Functional effectiveness
4) Product's Resource Utilization and Economy;
   - Energy efficiency/power consumption
   - Use of renewable source of energy
   - Material utilization
   - Purchase/market value
   - Installation and training cost
   - Operational cost (including labour cost, capital cost, etc.)
5) Product's Manufacturability;
   - Manufacturing methods
   - Assembly
   - Packaging
   - Transportation
   - Storage
6) Product's Recyclability/Remanufacturability;
   - Disassembly
   - Materials separation
   - Recyclability
   - Disposability
   - Remanufacturing/reusability (including multiple use of materials and repeated material flow cycles).

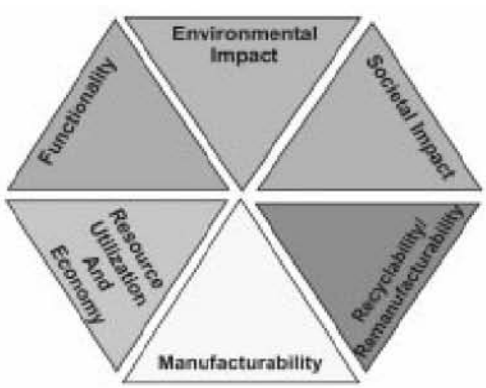


Fig. 1. Factors affecting product sustainability [34].

The above interacting elements and subelements need to be fully studied for their effects on product sustainability.Other influencing elements and subelements will be identified as appropriate. This systematic study should provide a solid foundation for involving relevant 'priority roles' and 'trade-offs', when this project is extended to the next level.

Our preliminary work in this area indicates that the ratings are needed at all three levels (subelement, element and overall) [34]. While the rating of each factor group contributes to the product's sustainability, the composite rating will represent the overall 'sustainability index' of a product—Product Sustainability Index (PSI). This overall product sustainability can be either in terms of a percentage level, or on a 0–10 scale, or on a letter grade such as 'A', 'B', 'C', etc. Figure 2 shows such an approximate product label to be formulated. Current research thus emphasizes the need for a universal and comprehensive trademark for easy and convenient societal application.

Figure 3 shows the integral role of all sustainability elements and subelements in generic form with equal weighting for each of the six major elements.

*Sustainable manufacturing processes*

The primary focus in identifying and defining the various contributing elements and subelements of manufacturing process sustainability is to establish a unified, standard scientific methodology to evaluate the degree of sustainability of a given manufacturing process [35]. This evaluation can

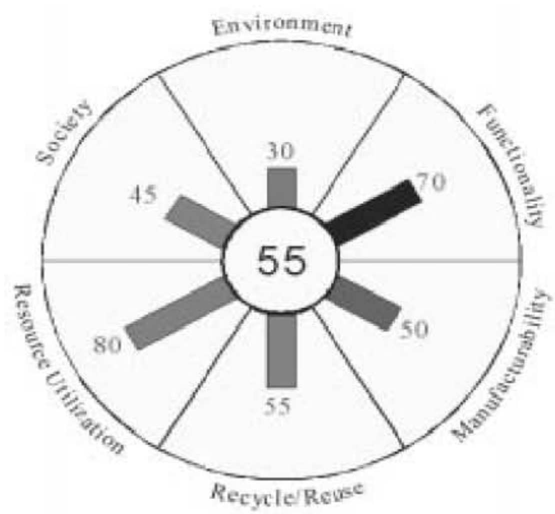


Fig. 2. Proposed sustainability label for manufactured product [34].


Fig. 3. Integral elements of design for sustainability.

be performed irrespective of the product life-cycle issues, recycling, remanufacturability, etc., of the manufactured product. Manufacturing processes are numerous, and depending on the product being manufactured, method of manufacture, and their key characteristics, these processes differ very widely. This makes the identification of the factors/elements involved in process sustainability and the demarcation of their boundaries complex. For example, if the production process of a simple bolt is considered, it goes through a few clearly defined production stages; bolt design, tool/work material selection, metal removal/forming, finishing, packaging, transporting, storage, dispatching, etc.

It is extremely difficult to consider all of these stages in evaluating manufacturing process sustainability even though these processes either directly or indirectly contribute to it. Also, the processing cost largely depends on the method used to produce the part/component and the work material selected. In a never-ending effort to minimize the manufacturing costs, the industrial organizations are struggling to maintain the product quality, operator's and machine safety, and power consumption. If the processing includes the use of coolants, lubricants, emission of toxic materials or harmful chemicals, this poses environmental, safety and personnel health problems. In general, among the various factors, the following six factors can be regarded as significant to make a manufacturing process sustainable.

*1) Energy consumption*

Measured during manufacturing operations to observe the power consumption level and this can be evaluated against the theoretical values to calculate the efficiency of the power usage during the operation. Significant work has been done in this area to monitor the power consumption rate and to evaluate energy efficiency.

*2) Manufacturing cost*

Optimal use of machines and tooling including jigs and fixtures can provide reduced manufacturing costs. Limited analytical and empirical models are available for this evaluation, but accurate calculations are highly complex and would require customized applications.

*3) Environmental friendliness*

Basic factor contributing to environmental pollution can be one or all of emissions from metal working fluids, metallic dusts, use of toxic materials, combustible or explosive materials. Compliance with the US Environmental Protection Agency (EPA) [36], Occupational Safety and Health Administration (OSHA) [37], and National Institute for Occupational Safety and Health (NIOSH) [38] regulations are required. Measurable parameters have been defined, and these measures are continually updated. Issues of major concern in environmentally benign manufacturing are presented in a major study involving international organizations and their practices [39].

*4) Operational safety*

The amount of unsafe human interaction during a manufacturing operation and the ergonomic design of the human interface are in focus for this category. Also, compliance with regulatory safety requirements is made mandatory. Statistical data on safety violations and the associated quantifiable corrective measures are usually being reviewed and updated.

*5) Personnel health*

Compliance with the regulatory requirements according to EPA, NIOSH and OSHA, on emissions from manufacturing operations and their impact on directly exposed labour can be the basis for this category of assessment.

*6) Waste reduction*

Recycling and the disposal of all types of manufacturing wastes, during and after the manufacturing process, are accounted for in this category. Zero-waste generation and hazard-free ejection into the environment are among the most emerging research topics. Scientific principles are still emerging with powerful techniques such as lean principles being applied, in quantifiable terms.

The basic driving force in sustainability studies as it applies to manufacturing processes is the recent effort in developing a manufacturing process sustainability index. The idea in developing this concept is to isolate the manufacturing process from the global picture of sustainability, and develop it up to the 'level of acceptance' for common practice in industry. This can be achieved in different stages. First, in the characterization stage, the most important measures of the rating system for manufacturing process sustainability must be identified and established through literature, in-house/field surveys and appropriate experimental work. Shown in Fig. 4 are some of the key parameters that can be considered typically in a machining process [35].

These observations and existing modelling capabilities will then be used to model the impact of the manufacturing process on the contributing major sustainability parameters. A hybrid model-

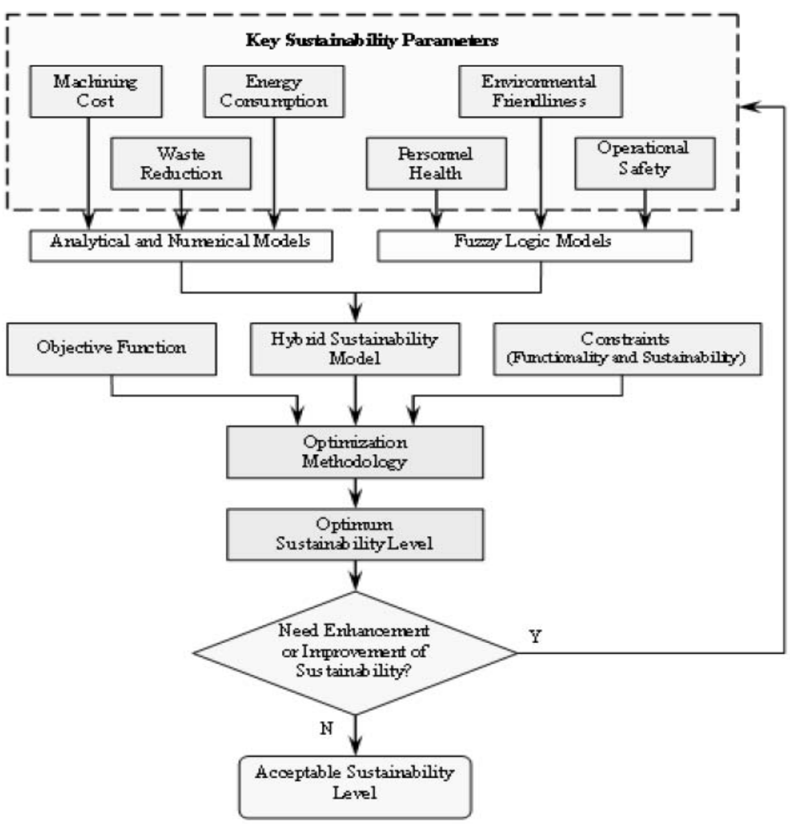


Fig. 4. Sustainability evaluation of manufacturing processes [34].

ling technique involving analytical and numerical methods, coupled with empirical data and artificial intelligence techniques must be developed to scientifically quantify the influence of each parameter. Then, the modelled production process can be optimized to achieve a desired level of sustainability with respect to constraints imposed by all involved variables. These optimized results can then be used to modify existing processes and enhance the manufacturing performance with respect to the main factors considered [40].

Finally, the optimized results can be used in defining the sustainability rating for the specific manufacturing process. In establishing this final sustainability rating, weighing factors can also be used to bring out focused evaluation and to serve the customized application.

*Systems perspective for sustainability*

The manufacturing systems planning aspects of processes, process logistics and the overall infrastructure would be needed for design and manufacture of products. In the context of sustainability, it is expected that the overall manufacturing system becomes sustainable in order to provide required sustainability support for the entire production cycle. Over the years, several technologically advanced manufacturing system concepts have emerged with tremendous capabilities for high productivity in the manufacture of high quality products at low cost. Unfortunately, these advances have not yet been adequately embraced. Product and process sustainability concepts within the application boundaries, have been developed with only the exception of lean manufacturing techniques which are primarily aimed at waste minimization and improved system logistics to provide greater productivity, an aspect which is included in our sustainability concepts for products and processes. Also, sustainable quality systems including the self-learning and human-based methodologies that pose significant variability in product and process quality need to be devised and implemented. Sustainable manufacturing systems of the future will be comprehensive systems facilitating the overall logistics needed for sustainable manufacture of sustainable products.

There is a need for developing sustainability criteria for manufacturing systems to represent the level of sustainability built in the manufacturing system by taking into account several major contributing factors including the following:

1) waste minimization (inventory levels);
2) human-machine interfaces and their interactions;
3) manufacturing costs;
4) maintenance of machines and equipment;
5) production flow and cycle time factor;
6) predictable product and process quality;
7) agility/reconfigurability of the manufacturing system.

## PROPOSED CURRICULUM DEVELOPMENT

The proposed curriculum in sustainability engineering is based on the strength of partnership among the three major participants: university, industry and state and federal organizations. Societal and environmental benefits, along with the economic gains are achievable with this strategic partnership, which brings in education and training as the major linkage as shown in Fig. 5.

Traditional educational programmes are evolved around the need for educating engineers and scientists with the basic knowledge on physical and natural sciences, engineering materials, product design engineering and manufacturing sciences. These disciplines are taught in isolation and with no significant exposure to real world applications. The new curriculum will focus on multi-disciplinary, interconnected and environmentally and societally-relevant subjects knitted together to form the fabric of 'sustainability engineering'. Significant emphasis will be placed on developing appropriate models for various elements such as environment, economy, societal benefits, etc., along with a thorough understanding of the natural cyclic systems representing the biocomplexity and reusable material bases including recyclability of materials. Design for sustainability principles will be taught to cover all relevant elements of practical sustainability such as disassembly, recovery, reuse, safety and maintenance of products and processes. Also, the significance of marketing, innovation, management, ethics, regulations, etc., will be covered in this proposed approach to provide a much broader knowledge base for next generation design engineers as shown in Fig. 6.

Also, manufacturing engineering science courses will include material on process performance enhancement, sustained quality, improved health and safety along with knowledge on cleaner manufacturing processes. The progression of cumulative learning at undergraduate and graduate levels extending up to Ph.D. is shown in Fig. 7.

The fundamental difference between this proposed method and the current methods is that


Fig. 5. Strategic partnership for education and training.

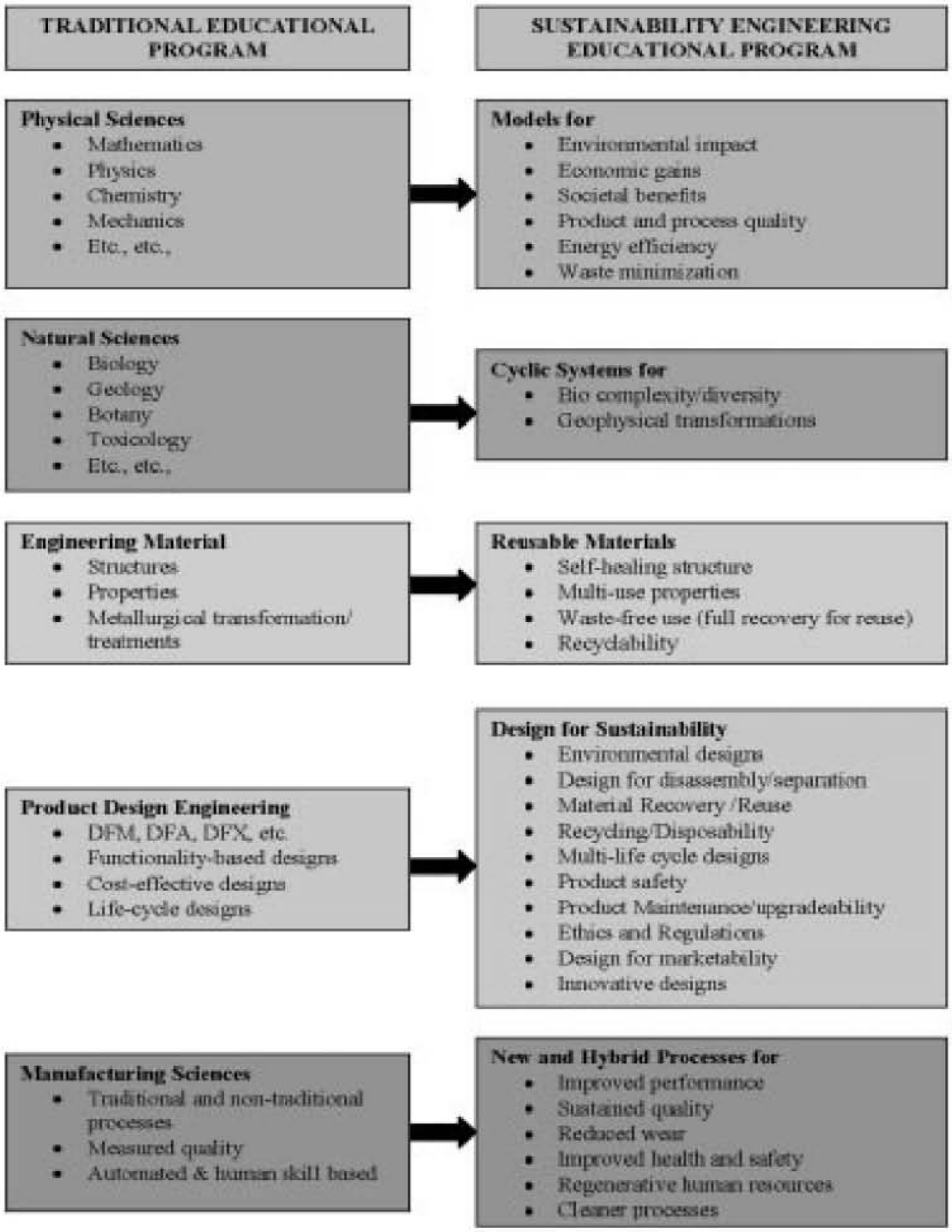


Fig. 6. Paradigm shift for sustainability engineering education.

the role and responsibility of engineers and the history of product development as it evolved over centuries to empower human civilizations is emphasized in Year 1 of the undergraduate curriculum. Also, in Year 2, undergraduates will learn industrial growth elements, technological innovation and workforce development needs. Academic learning of sustainability principles in product design and manufacture begins in Year 3 with students undertaking industry-based projects and being involved in industrial outreach programmes. M.S. and Ph.D. programmes are proposed to focus on basic and applied research, model development for sustainability applications in products and processes and industry-based project work including internships in industry.

The proposed curriculum is an extended programme beyond the traditional degree programmes shown above. Fig. 8 shows the five basic elements of this curriculum structure featuring:

1) a new curriculum based on instruction, lab work and projects at undergraduate and graduate levels;

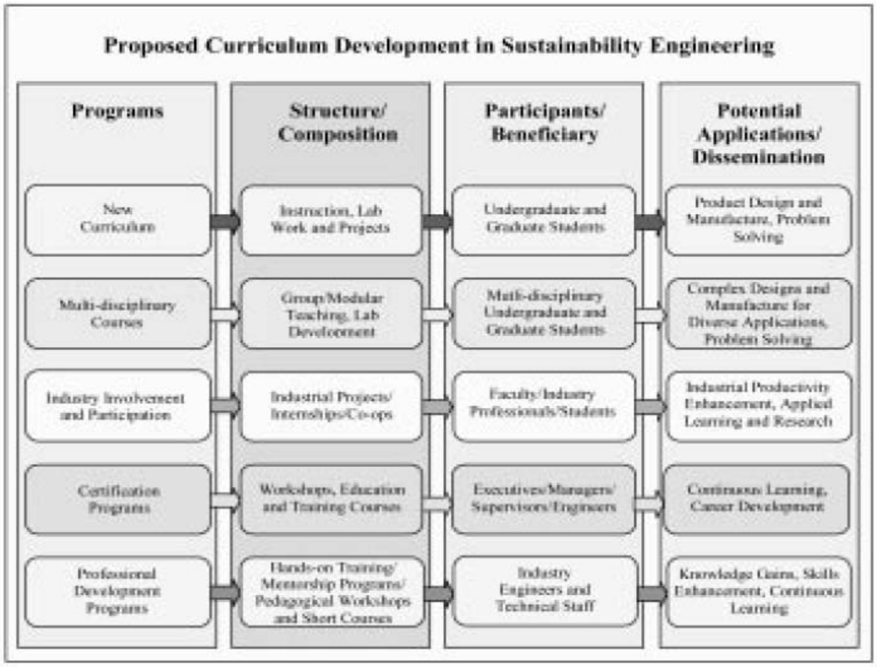


Fig. 7. Basic elements of proposed curriculum.

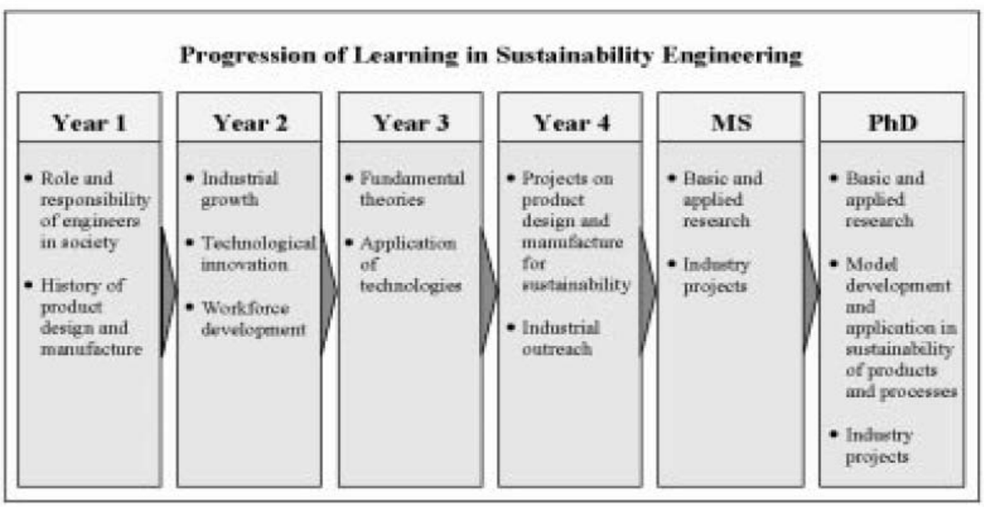


Fig. 8. Progression of cumulative academic learning in sustainability engineering.

2) multi-disciplinary courses in the current curriculum to provide a broader perspective on sustainability;
3) industry involvement and participation;
4) certification programmes for engineers working in industry;
5) professional development programmes such as short courses.

## CASE STUDY

*Developing and implementing a new graduate course on sustainable products, processes and systems*

A recent effort to introduce a new course on sustainable products, processes and systems at graduate level within the current structure of the

Masters degree programme in Manufacturing Systems Engineering at the University of Kentucky is summarized below. This course was developed and implemented by a group of seven faculty and three technical staff from the university, with participation from a few local industry groups representing the automotive, consumer electronics and equipment manufacturing segments of manufacturing industry.

A range of topics relating to sustainability in design and manufacture was covered through specialized lectures in class by the participating faculty. This included:

- Fundamentals of sustainable products, processes and systems;
- Product life-cycle design and manufacture;
- Products assembly and disassembly methods;
- Product and process design for environment;
- Product design and manufacture for functionality;
- Engineering economics for sustainable manufacture;
- Safety and ergonomics for sustainability;
- Organizational structure for sustainable systems;
- Societal aspects of sustainability;
- Technical communication;
- Professional ethics.

These lectures also included several case studies drawn from automotive, aerospace and consumer electronics product design and manufacture and specific sustainability applications.

The students were divided into four project groups and assigned with industry-based projects requiring sustainability improvement in product design and manufacture. Product and process innovation was an expected element of the project. Each project group was jointly advised/supervised by a faculty and a senior engineer from the industry. Students were able to demonstrate the economic, environmental and societal benefits, in some quantifiable terms, from the project outcomes. Course evaluation was made as follows:

- Project Plan (Week 3)
  10% (Team work)
- Progress Reports (3) (Week 5, 9, 12)
  30% (Individual effort)
- Mid-term Presentation
  10% (Individual effort)
- Final Report and Presentation (Finals Week)
  50% (Team work)

## CONCLUSIONS

We have highlighted the need for significant changes in the traditional curriculum for product design and manufacture to accommodate basic sustainability principles, beyond the well-known life-cycle analysis, and their applications. Sustainability evaluation methods are shown for manufactured products and manufacturing processes, along with a systems perspective for sustainability applications in manufacturing organizations. The proposed new curriculum provides a structure for undergraduate and graduate education, multidisciplinary courses, industry involvement and partnerships, certification and professional development programmes for industry-based engineers.

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