Proceedings of DETC'02
ASME 2002 Design Engineering Technical Conferences and Computers and Information in Engineering Conference
Montreal, Canada, September 29-October 2, 2002

DETC2002/DFM-34177

BIOMIMETIC CONCEPT GENERATION APPLIED TO DESIGN FOR REMANUFACTURE

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ABSTRACT

This paper applies a biomimetic design method to generate concepts for design that facilitates remanufacture. Biomimetic design fully or partially imitates or evokes some biological phenomenon. A method for identifying and using biological analogies for engineering problems was introduced in an earlier paper. This initial method was tested on an example in design for remanufacture. Here, the method is further developed and used to find more biomimetic solutions for the same problem in design for remanufacture. While the example problem is in remanufacture, the method can be used to develop biomimetic concepts for engineering design in general.

The paper first summarizes previous efforts in developing and testing the biomimetic concept generation technique. Next described are the differences in the method that are used for this paper, including the increased importance of strategies to help identify promising analogies. Results of applying the modified method to design for remanufacture are documented.

Keywords: biomimicry, analogy, function, remanufacture

NOMENCLATURE

<u>Biomimetic design</u>: Design that, fully or partially, imitates or evokes some biological phenomenon.

<u>Biological phenomenon</u>: Any natural phenomenon pertaining to the biological sciences including all levels of biological organization shown in Table 1.

INTRODUCTION

The context for biomimetic design includes the use of analogies, as well as related and unrelated stimuli in concept generation. Analogies range from those available in a related product or application, to abstract phenomena whose relation to the problem is not immediately obvious. The use of unrelated stimuli includes relating the problem at hand to a random subject, with the goal of generating novel solutions during this process. Biological analogies lie somewhere between related and unrelated stimuli. The analogies are sought based on functional similarities, and are thus related, but analogies found at different levels of the biological organization shown in Table 1 may be quite abstract, the use of which may encourage different perspectives on the problem.

Biological phenomena hold a vast amount of ideas that could be useful to engineers during design concept generation. Advantages of biological systems are discussed by Paturi (1976), Galbraith *et al.* (1989), Benyus (1997), Affholter and Arnold (1999), and David (1999). While many cases of biomimicry exist, several started with an interesting biological phenomenon that was developed into a useful concept. Therefore, little insight is offered on how to find appropriate biological analogies given an engineering problem as the starting point. Several other instances of biomimicry copy fairly obvious examples, e.g., a fish for underwater robotic movement or a bat or bird for a flapping wing ornithopter. It is likely that the ability to locate biological analogies beyond the obvious would help generate novel engineering concepts. We believe that a systematic search for analogies at multiple levels of biological organization shown in Table 1, i.e., from the molecular to the ecological level, would encourage different perspectives on problems and thus lead to novel solutions.

An earlier paper (Vakili and Shu, 2001) introduced a biomimetic concept generation method to address the above shortcomings of existing biomimicry. The preliminary method was tested on a problem in design for remanufacture.

In this paper, we further develop the method and apply it to the same problem in design for remanufacture so that the results can be compared with those obtained previously.

The main components of the paper include:

1. Summary of our previous efforts towards generalizing biomimetic concept generation.
2. Description of our subsequent progress, resulting benefits and additional challenges.
3. Documentation of applying the developed method to the continued example in design for remanufacture.

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Table 1: Biological Organizational Levels.

Organizational Level	Definition	Examples
Molecule	Two or more atoms joined by covalent bonds or ionic attractions.	Proteins, DNA, enzymes
Organelle	One of several formed bodies with specialized functions suspended in the cytoplasm found in eukaryotic cells.	Mitochondrion, cell nucleus
Cell	The lowest level of organization where all the properties of life appear.	Neuron, red blood cell
Tissue	An integrated group of cells with a common structure and function.	Brain tissue, muscle tissue, bone
Organ	A specialized center of body function composed of different types of tissues.	Brain, kidney, heart
Organ System	An organized group of organs that carries out one or more body functions.	Nervous and digestive systems
Organism	A complete living being composed of one or more cells.	A deer, tree, single-cell organism
Population	A group of individuals of one species that live in a particular geographic area.	Bacterial culture, all deer in forest
Community	All the organisms that inhabit a particular area; an assemblage of populations of different species living close enough together for potential interaction.	All animals, plants, bacteria, fungi etc., in a particular area
Ecosystem	All the organisms in a given area with the abiotic factors with which they interact; a community and its physical environment.	A forest, a pond
Biosphere	The entire portion of the earth that is inhabited by life. The sum of all the ecosystems of the planet.	Planet Earth

PREVIOUS WORK

An earlier paper introduced a strategy for biomimetic concept generation that involves searching for biological analogies to help solve engineering problems (Vakili and Shu, 2001). Functional requirements of the engineering problem are identified and used to derive keywords and their synonyms. These keywords and synonyms are searched for in a biological context to identify phenomena related to the functional requirements of the engineering problem. Since the flow of the biological system is likely completely different from the flow of the engineering system, searching by function identifies potentially useful analogies but may require some effort to relate back to the engineering system.

Since many engineers may not have sufficient background in biology to think of analogous phenomena for their problem, a systematic search method on a biological information source would be useful. In addition, a systematic search method may identify analogies beyond the obvious ones in an objective and repeatable manner.

The initial source of biological phenomena was chosen to be *Life: The Science of Biology* (Purves *et al.* 1998), which was the reference text for BIO 150Y, the introductory course in biology at the University of Toronto. This introductory text is appropriate for two reasons. First, those lacking a background in biology can easily understand the text. Second, the text includes many organizational levels in biology shown in Table 1, so that analogies are not limited to any particular organizational level. One advantage of our method is that the entire text need not be read in search of appropriate analogies.

Because it is unlikely to find engineering keywords in the index of a biology text, the glossary of the text was converted into computer searchable format to act as a bridge between engineering and biological terms. The keywords were then searched for in the glossary. Synonyms to the keywords were generated and also sought to increase the chances of finding matches. Instances of matches in either the definition or term of a glossary entry identified relevant phenomena that can then be further researched using this and more advanced texts.

As mentioned, the example used to illustrate the preliminary biomimetic concept generation method is on design for remanufacture. Remanufacturing is an end-of-life process where the product is disassembled and parts of it are cleaned, inspected and are reused instead of being recycled for their material (Lund, 1996). Design that facilitates remanufacture can be accomplished by designing for any of the above steps of remanufacturing, e.g., disassembly, cleaning etc. However, since the most essential goal of remanufacture is to reuse parts, design that facilitates part reuse is fundamental to supporting remanufacture (Shu and Flowers, 1999).

A search of the glossary was performed for the functions (or keywords) remanufacture, refurbish and their synonyms. The majority of matches that were found in the glossary were related to DNA replication. A particularly promising phenomenon identified was excision repair of DNA. More details on excision repair were found in the initial text and in a more advanced text, which led to the concept of failure-induced deformation in a product to facilitate removal of the defective zone, enabling easier replacement during remanufacture.

In the initial work, almost all the matches found were at the molecular level. This is likely because only the glossary was searched for occurrences of the engineering keywords and their synonyms. The glossary, in addition to being a small subset of the entire text, may only contain terms that require definition, and not include less technical terms such as healing and regeneration.

Not being able to easily search the entire text was recognized as a limitation in the initial study. For this paper, the entire text was made available to search for instances of the engineering keywords and their synonyms. The advantages and challenges of searching the entire text instead of only the glossary are explored using the same keywords and synonyms in design for remanufacturing that were used in the earlier work.

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Table 2: Matches to Keywords, Synonyms, and Related Words Found in Purves *et al.* (2001).

Keywords	Synonyms	No. of matches	Organizational levels
Remanufacture	Remanufacture	None	
Refurbish	Refurbish	None	
	Renew	5	Molecule, Organelle, Organism
	Modernize	None	
	Refresh	None	
	Rejuvenate	None	
	Renovate	None	
	Restore	24	Molecule, Organelle, Cell, Organ system, Organism, Ecosystem
	Update	None	
Renew (related words)	Make over	None	
	Remodel	11	Molecule, Organism, Tissue
	Mend	133	Molecule, Population
	Rebuild	None	
	Repair	52	Molecule, Organelle, Cell, Tissue, Organ system, Organism, Community, Ecosystem
	Correct	67	Molecule, Organelle, Tissue, Organ, Organ system, Organism, Community, Ecosystem
	Rectify	1	Population
	Reform	3	Organism
	Revise	3	Molecule, Organism
	total	299	

FURTHER EFFORTS TOWARDS GENERALIZING BIOMIMETIC CONCEPT GENERATION

An updated edition of the *Life* text (Purves *et al.*, 2001) was used to search for the same two keywords, *remanufacture* and *refurbish*, synonyms, as well as related words for the synonym *renew* used in (Vakili and Shu, 2001).

Table 2 lists these words, the number of matches found for each word, and organizational levels at which matches were found searching the entire text.

Similar to previous results of searching only the glossary, searching the entire text for the engineering terms *remanufacture* and *refurbish* did not result in any matches. However, the search for the synonyms and related words in the entire text resulted in a much larger number of matches than was found with the glossary. The large number of matches is a new challenge, requiring that the relevant matches be distinguished from those that are less useful.

The majority of the previous matches found searching the glossary only were related to DNA replication. As expected, the search of the entire text resulted in matches from more diverse organizational levels and a much broader scope of topics. Overall, 299 matches were found in the text for the keywords, synonyms and related words.

In addition to finding a larger number and variety of relevant matches while searching the entire text instead of only the glossary, a proportionally larger number and variety of irrelevant matches were found. Following up on each match, e.g., reading the section of the book containing the matched word requires effort, much of which may be wasted when there are a large number of irrelevant matches. Irrelevant matches are those where it is clear from the sentence containing the searched word, that the corresponding concept does not require further investigation, whereas relevant matches motivate further reading in the *Life* text and, if necessary, in more advanced texts. Characteristics of irrelevant matches are identified to work towards systematically removing, or at least, giving less priority to these matches.

DISTINGUISHING IRRELEVANT MATCHES

The following characteristics were observed to be common among the irrelevant matches.

1. Matches where the searched word found in the text had a different meaning from that in the problem.
2. Matches where the searched word was found as part of a different word.
3. Matches where the searched word was used in the context of a non-physical attribute or a function unrelated to the problem.

Clarification of the above characteristics using examples in the design-for-remanufacture problem follows.

1. Search word found with a different meaning

Often a searched word is found in the text with a meaning different from the meaning in the problem. For example, one of the matches to the word *correct* in Purves *et al.* (2001) is:

> A clever experiment conducted by Matthew Meselson and Franklin Stahl convinced the scientific community that semiconservative replication is the **correct** model.

Here the word *correct* is used to mean *accurate*, not *repair* or *rectify*, two of the words in the list of related words to *renew* from which *correct* was taken. In cases such as this, it is clear that the matches are not suitable and they should not be looked into for more details. Of the total 299 matches that were found in the full-text search, 61 matches fell under this category and could be disregarded.

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2. Search word found as a part of a different word

The search was not limited to finding whole words as this would result in missing many useful matches. For example, instead of looking for only occurrences of the word *mend*, also of interest are occurrences of *mending, mended, etc.*

However, this resulted in matches where the letters of the search string were a part of a word with a completely different meaning. For example, the search for the string *mend* resulted in 117 matches with Gregor **Mend**el, a pioneer in genetics, whose name occurs in the text 117 times. With other such examples, 135 of 299 matches fell under this category.

3. Search word refers to unrelated phenomena

Categories 1 and 2 represent situations where the search word was found, but the matched word or word of which it was a part had a meaning different from that used for the problem. In this category, the matched word is used with the intended meaning but in contexts that are not relevant.

Since our example concerns the repair of physical parts, matches for correction of nonphysical entities are less useful. For example, found in a section on *Identifying photosynthetic reactants and products*, in Purves *et al.* (2001):

> In this **revise**d equation, there are now sufficient water molecules to account for all the oxygen gas produced.

The word *revised* refers to an equation, which is not a physical entity, and therefore it is not useful for finding analogies to the remanufacturing problem. Out of the 299 matches, 27 matches fell under this category.

Remaining matches

While the three above characteristics can be used to identify irrelevant matches, there were 13 matches whose relevance was unclear to us from the sentence containing the matched word. This is due to our lack of knowledge of the biological phenomenon referenced. Relevance in these cases was determined by reading the sections containing the match.

Finally, 63 of the 299 matches remain. Of these, 32 were related to DNA repair, already used in Vakili and Shu (2001). Table 3 compares the number of matches that were relevant, irrelevant for one of the above reasons, or whose relevance was unclear to us. Parentheses contain the number of matches related to DNA repair.

Table 3: Categorization of relevance of matches.

Keyword/ synonym	Total number of matches	Irrelevant			Rele-vant	Un-clear
		1	*2*	*3*		
Renew	5	2		3		
Restore	24	7		9		8
Remodel	11			1	6	4
Mend	133		132		1 (1)	
Repair	52			4	47 (29)	1
Correct	67	52		6	9 (2)	
Rectify	1			1		
Reform	3		3			
Revise	3			3		
Total	299	61	135	27	63 (32)	13

NATURAL LANGUAGE PROCESSING

While the full-text searches performed for this paper resulted in many more matches then searching the glossary alone in previous work, the ability to distinguish the relevant matches from the irrelevant is required for the biomimetic search method to be more practical than cumbersome. The characteristics of irrelevant matches described previously can be automatically identified using concepts and tools developed in the field of natural language processing.

Goals of natural language processing include automatic recognition of linguistic information (e.g., part of speech, phrase structure, predicate argument structure and word sense disambiguation) from existing collections of manually annotated writings, referred to as corpora (Brill, 1995). Existing linguistic information from manually annotated corpora is used to train natural language processing systems. Brill (1995) developed a tagger that assigns a part of speech for each word in the text of interest, based on rules learned while minimizing errors between automatic and manual annotation of training text. For example, Brill tagging performed on a match from the biomimetic search for the keyword *remodel* follows.

> Bone/NN is/VBZ continually/RB being/VBG **remodel**ed/VBN by/IN osteoblasts/NNS ,/, which/WDT lay/VBD down/RB new/JJ bone/NN ,/, and/CC osteoclasts/NNS ,/, which/WDT erode/VBP bone/NN

> Where: VBN=verb, past particle; VBZ=verb 3rd person singular present; VBG=verb gerund or present particle; VBD=verb past tense; VBP=verb non-3rd person singular present; NN=noun singular or mass; NNS=noun plural; RB=adverb; IN=preposition or subordinating conjunction; JJ=adjective; WDT=wh-determiner; CC=coordinating conjunction (Brill, 1995).

A Brill tagger can be useful for distinguishing relevant matches in the biomimetic search. For example, the word *correct* can be a verb meaning to repair, or an adjective meaning free from error. Using the Brill tagger, a search could be performed for only verb forms of the word *correct*. However, part of speech alone is not enough to distinguish relevant from irrelevant matches, e.g., the specific meaning of a keyword is not always defined by part of speech.

WordNet is a lexical database for the English language where words are organized into synonym sets that share the same meaning, or sense (Miller, 1990). WordNet can be used to identify the multiple meanings associated with keywords to help distinguish between uses of these words that more closely match the meaning required by the problem. For example, the keyword *renew* has two WordNet senses, where the first sense is more relevant for our problem:

1. To re-establish on a new, usually improved, basis or make new or like new.
2. To cause to appear in a new form.

In addition to senses, WordNet can also be used to identify synonyms, hypernyms ("word" is a kind of ...) or hyponyms (… is a kind of "word") for words of interest.

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CONCEPT GENERATION

Previous sections identified strategies to possibly eliminate, either manually or automatically, potentially large numbers of irrelevant matches. This section uses the relevant matches found at different levels of biological organization, in addition to the molecular level of the DNA repair analogy used in previous work (Vakili and Shu, 2001), to illustrate how concepts can be developed from the analogies.

Cell – Plants seal off infected parts to limit damage

One match for *repair* in Purves *et al.* (2001) was found in a section entitled, *Plants seal off infected parts to limit damage*. This section explains how plants protect themselves from environmental challenges such as pathogens or herbivores. Relevant sections of Purves *et al.* (2001) follow:

> The defense systems of plants and animals differ. Animals generally **repair** tissues that have been infected. Plants, on the other hand, do not make **repair**s. Instead, they seal off and sacrifice the damaged tissue so that the rest of the plant does not become infected. …
>
> One of the plant's first defensive responses is the rapid deposition of additional polysaccharides to the cell walls, reinforcing a barrier to invasion by the pathogen. These polysaccharides block the plasmodesmata, limiting the ability of viral pathogens to move from cell to cell. The polysaccharides also serve as a base upon which lignin may be laid down, enhancing the mechanical barrier and making cells inhospitable to some pathogens due to the toxicity of lignin building blocks.

Concepts used from above are first, plants seal off damaged tissue to isolate the pathogen from the rest of the plant, and second, the substance used for sealing is already contained in the plant and reacts to the presence of a pathogen.

A problem in the remanufacture of toner cartridges is that the glue on the seal that holds toner in its compartment degrades, causing the seal to detach as shown in Figure 1, and toner to leak into the rest of the product. The entire cartridge is usually discarded because of toner contamination. If a substance is placed in or around the seal that reacts with the leaking toner to provide a secondary seal, than the damage can be more easily contained. Alternative options that also require further development may include a mechanical seal that is actuated by toner presence or glue degradation.

Figure 1. Unglued seal on toner cartridge.

Organ – Corrective lenses for eyes

The search for the word *correct* in Purves *et al.* (2001) resulted in a number of matches, one of which is contained in a section entitled, *Image-forming eyes evolved independently in vertebrates and cephalopods,* that describes the differences between the eyes of vertebrates and cephalopods. Below is the relevant section from Purves *et al.* (2001) explaining how mammals and birds alter the shape of the lens to focus images.

> The lens is contained in a connective tissue sheath that tends to keep it in a spherical shape, but it is attached to suspensory ligaments that pull it into a flatter shape. Circular muscles called the ciliary muscles counteract the pull of the suspensory ligaments and permit the lens to round up. With the ciliary muscles at rest, the flatter lens has the correct optical properties to focus distant images on the retina, but not close images. Contracting the ciliary muscles rounds up the lens, changing its light-bending properties to bring close images into focus (Figure 45.22). As we age, our lenses become less elastic and we lose the ability to focus on objects close at hand without the help of **correct**ive lenses. As a consequence, most adults over the age of 45 need the assistance of bifocal lenses or reading glasses to compensate for their lost ability to accommodate.

The concept used from this analogy is that corrective lenses restore function by adding an auxiliary device. Similarly, in remanufacture, adding a different system or feature to compensate for the poor functionality of the damaged feature may be used to restore function without repairing the damage.

Another problem in the remanufacture of toner cartridges is that the slot for snap fits that hold together two halves of the outer shell of a toner cartridge tends to become damaged during disassembly for remanufacture. Figure 2 shows a hole to the left of the damaged snap fit that may be used to install a threaded fastener that restores fastening function without repairing the slot. To generalize, first, features or systems that will have reduced functionality over time are identified, and second, the system is designed so that a different sub-system could be added to restore function without repairing the damaged feature.

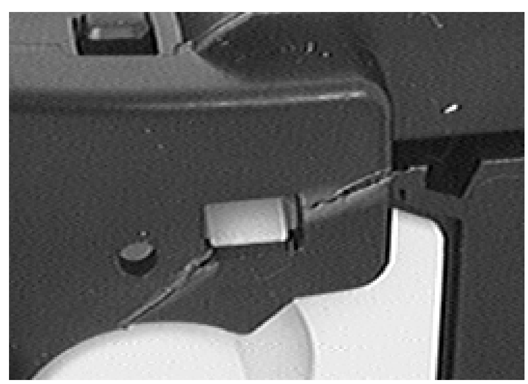

Figure 2. Extra hole in toner-cartridge housing.

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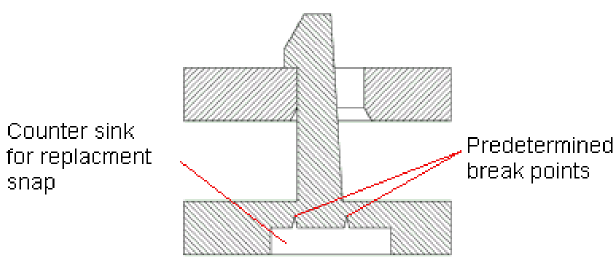
Organ system – Fainting

One of the matches for the word *correct* in a section entitled, *Blood flows back to the heart through veins*, in Purves *et al.* (2001) is as follows:

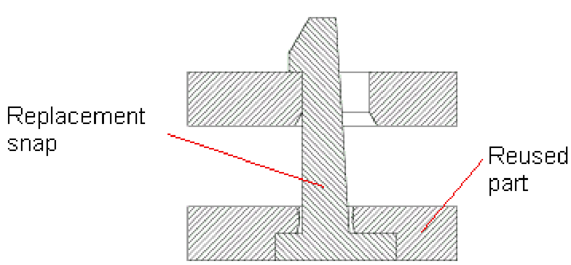
> Blood must be returned from the veins to the heart so that circulation can continue. If the veins are above the level of the heart, gravity helps blood flow, but below the level of the heart, blood must be moved against the pull of gravity. If too much blood remains in the veins, then too little blood returns to the heart, and thus too little blood is pumped to the brain; a person may faint as a result. Fainting is self-**correct**ing: A fainting person falls, thereby moving out of the position in which gravity caused blood to accumulate in the lower body.

The concept used from this analogy is that fainting protects the body from further damage by causing limited breakdown that allows the body to recover. Similarly, products can be designed such that anticipated failure occurs in a way that facilitates repair.

In many products, snap fits are used as a fastening method due to their ease of assembly. However, snap fits frequently break and are difficult to repair during remanufacture. Figure 3 shows a snap fit that is redesigned with break points so that failure occurs in a predetermined manner to facilitate the repair of such parts.



a. Snap fit redesigned with counter sink and break points



b. Redesigned snap fit after failure and refurbishment

Figure 3. Redesigned snap fit to facilitate repair.

Organism – Plants replace damaged parts

Another design concept for remanufacturing was related to the same match that was used in the cell-level example. The search for the word *repair* led to a match in Purves *et al.* (2001) that can also provide an analogy at the organism level:

> The defense systems of plants and animals differ. Animals generally **repair** tissues that have been infected. Plants, on the other hand, do not make **repair**s. Instead, they seal off and sacrifice the damaged tissue so that the rest of the plant does not become infected. This approach works because most plants, unlike most animals, can replace damaged parts by growing new stems, leaves, and roots.

In the cell-level example, the analogy focused on the ability of plant cells to isolate damage. The analogy at the organism level derives from the ability of plants to add new parts to replace the damaged ones. Applying this analogy to products involves adding a similar part to replace a broken feature, without repairing the broken feature or replacing the entire part that contained the feature.

For example, Figure 4, from the repair manual of a photocopier remanufacturer, shows the inside features of a photocopier door that is opened to remove a paper jam. In the process of clearing the paper path, several levers are moved. These levers must be replaced before another photocopy is made. The function of the cone shown is to prevent the door from being closed without having first replaced the levers. Due to its function, the cone is frequently damaged. During remanufacture, a portion of the damaged cone is cut away and a new cone is glued over it.

To facilitate this process, the door could be designed with features to assist the fitting or installation of planned replacement parts. For example, the inclusion of perforations at the dotted line shown in Figure 4 that indicate the location where the damaged feature is cut away would facilitate disassembly of the damaged feature. Of possible interest are abscission mechanisms that facilitate the separation of leaves, petals and fruits from a plant.

Generalizing this approach, features that are likely to fail should incorporate features to both facilitate disassembly and use of similar replacement parts in remanufacture.

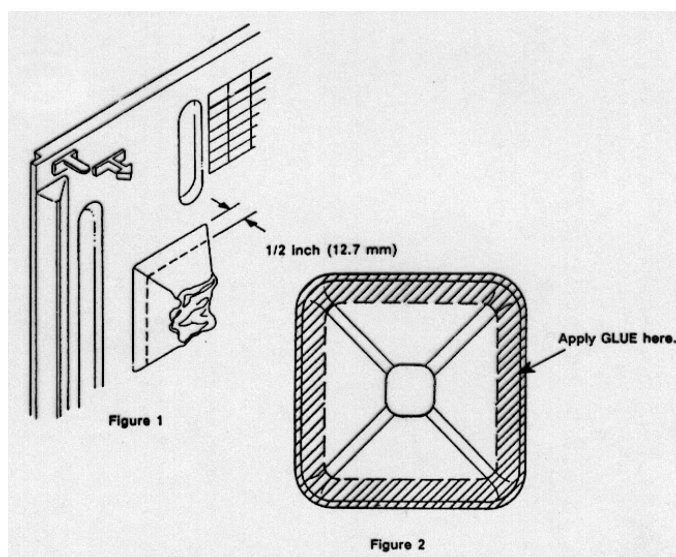


Figure 4. Refurbishment of photocopier door feature.

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Ecosystem – Restoring degraded ecosystems

The search for the word *restore*, in Purves *et al.* (2001), located the following match in a section entitled, *Restoring degraded ecosystems*:

> The world's largest restoration project is under way in Guanacaste National Park in northwestern Costa Rica. Its goal is to **restore** a large area of tropical deciduous forest – the most threatened ecosystem in Central America – from small fragments that remain in an area converted mostly to pastures.

The concept to be used from this analogy is that restoration involves a process that builds upon small fragments of preserved forest until they meet to form a large continuous forest. A similar concept can be used for restoring parts in remanufacture.

For example, Figure 5, from the manual of a photocopier remanufacturer, shows a repair method for a photocopier panel that requires the embedding of mesh substrate into a section with a hole. The screen acts as support for filler material to replace the lost material. That is, replacement material bonds onto the screen, and more replacement material is bonded until a continuous panel is restored. The correct positioning of this screen in the panel is important for the structural and aesthetic results of the repair. Design that facilitates this process further could involve having a screen already embedded in portions of the product that are likely to fail, so that effort need not be expended in positioning the screen during remanufacture. To generalize, provide a base or substrate upon which anticipated repairs may build.

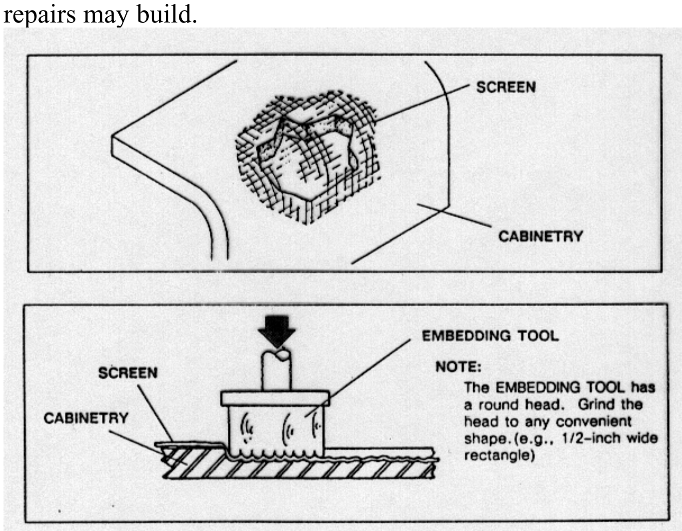

Figure 5. Refurbishment of photocopier panels.

CONCLUSIONS

Concepts in design for remanufacture were either generated based on, or related to, analogies identified at different levels of biological organization by a systematic search process. Previous work (Vakili and Shu, 2001) searched keywords, synonyms and related words describing remanufacture in the glossary of Purves *et al.* (1998) to identify relevant analogies. An analogy was found at the molecular level, specifically repair mechanisms during DNA replication, that led to a concept that would facilitate remanufacture. This paper described the search of the same keywords, synonyms and related words in the entire Purves *et al.* (2001) text.

As expected, the benefits of an entire-text search were that more matches were found, and that matches were found in several biological organization levels, from the cell to the ecosystem, not located searching only the glossary. The major drawback of the expanded search as performed is that more irrelevant matches were also found. The amount of irrelevant matches threatens the practicality of the search method. Therefore, the characteristics of such matches were identified so that their systematic removal may be incorporated in future search strategies.

Concepts for design to facilitate remanufacture were developed from the relevant matches found to illustrate the use of analogies from different levels of biological organization. While analogies at some organizational levels were related to existing processes, suggestions of how to further facilitate these processes were made. All concepts generated support the essential goal of remanufacture, the reuse of parts.

This work demonstrated that the search method is capable of locating useful analogies at multiple levels of biological organization for a given engineering problem in a systematic manner. Future work aims to refine the search method and involves the use of tools developed for natural language processing that may help to distinguish relevant matches.

ACKNOWLEDGMENTS

The authors thank William Purves for making available to us the *Life* text, Andrew Shaw and Oscar del Rio for their roles in developing the search tool, and financial support of this work by NSERC (Natural Sciences and Engineering Research Council of Canada).

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