A Framework For Knowledge Intensive 'Artefact Life' Design

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Abstract: The *interaction* of an artefact with different life-phase systems can give rise to a number of consequences. 'Artefact' and 'life-phase system' design decisions can therefore result in *unintended consequences* that have a *propagation effect* across *multiple* life-phases such as manufacturing, use and disposal. Handling this phenomena *during* design is thus a necessity if designers are to generate 'life-oriented' solutions. However, the sequence of life-phases makes knowledge of such life-cycle consequences (LCCs) available *late*, after decisions have been committed. Thus, designers are frequently unaware of LCCs co-evolving with their solution, this making 'life-oriented' solution generation difficult to achieve. Designers are simultaneously under increasing pressures to deliver artefacts that cater for a *host* of total life-cycle issues. This paper concerns on-going research into the development of a knowledge intensive approach framework to handle this DFX phenomena *during* the synthesis of mechanical component life solutions. The framework collectively describes the concept of how a domain specific LCC knowledge model can be generated and operated to support this DFX problem, thereby contributing to the development of KICAD architectures.

Key words: DFX, design decisions, life-cycle engineering, design reuse

1. INTRODUCTION

Design decisions can result in *unintended consequences* that have a *propagation effect* [Borg 1999] across *multiple* life-phases such as manufacturing, use and disposal. In 'artefact life' design, solutions need to cater for *more* life-cycle issues. Thus, rather than a *narrow, segmented* and *late* ‘Design for X’ (DFX) approach, designers need to adopt a 'Design Synthesis for Multi-X' ($D_sF\Sigma X$) approach (Figure 1).

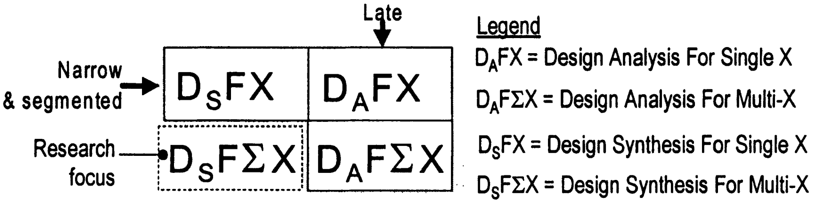

Figure 1 – Dimensions of a DFX approach

Such a $D_sF\Sigma X$ approach treats Xs, like life-phases (e.g. disposal) and performance measures (e.g. cost) in a *multiple* and *integrated* way during synthesis. However, this constitutes a problem, as DFX-methods should be used at the conceptual design stage [Andreasen et al. 1997] when the solution is still evolving. Also, current manual and computer based design approaches [Borg 1999], do not adequately support designers during synthesis in handling the phenomena of propagation effects, by *foreseeing* and exploring LCCs co-evolving with their *synthesis decisions* [Borg 1999]. As argued by [Tomiyama et al. 1998], for generating more added value, CAD systems must include the life-cycle knowledge. To address this situation for mechanical artefact life design, this on-going research is developing an approach to $D_sF\Sigma X$ - a computational ‘Knowledge of life-cycle Consequences’ (KC) framework, as discussed in this paper.

2. ‘ARTEFACT LIFE’ CONSEQUENCES PHENOMENA

A mechanical artefact can be considered as a decomposable system [Hubka et al. 1988]. In this structural view, an artefact consists of a number of elements (sub-assemblies, components, component elements), termed in this research *Product Design Elements (PDEs),* related to each other with *'part of'* relationships. The life-phases, *design, realization, use* and *disposal* forming a mechanical artefact’s life, involve the *re-use* of technical systems (e.g. manufacturing or maintenance systems) that realize the relevant transformation effects of that phase. These systems (e.g. milling machine) can be also decomposed into sub-systems (e.g. a workpiece holding device) termed in this paper as *life-cycle phase elements (LCPE).* As argued in [Borg 1999], the *interaction* of an artefact with either *natural* (e.g ocean) or *artificial* (e.g. milling machine) life-phase systems (Figure 2) can give rise to a number of *unintended life-cycle consequences (LCCs).* A $D_sF\Sigma X$ approach therefore requires that designers foresee what life-phase systems will be met during the life of an artefact and that they also foresee the outcome (consequences) of such interactions during design.

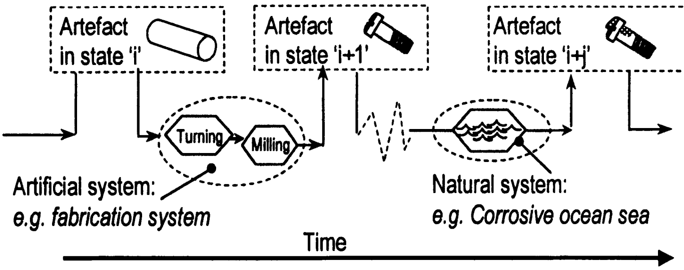

Figure 2. Interactions between artefact and life-phase systems

Due to the chronological order of life-phases, designers do not generally *acquire* experiential knowledge concerning LCCs resulting from artefacts interacting with different life-phase systems. Rather, such experiential LCC knowledge is *acquired* and *distributed* amongst various artefact life-actors (e.g. assembly operators, machining operators, users, servicing engineers) that are *distributed*, internally and externally to an organization. Therefore a $D_sF\Sigma X$ approach requires a vast amount of distributed LCC knowledge to be acquired, readily available and easy to access if it is to be explicitly utilized during synthesis decision-making. Understanding the phenomena of how LCCs are generated and propagated during synthesis is thus essential for the development of *Knowledge Intensive CAD* tools.

2.1 'Artefact Life' Design Decision-Making

Irrespective of the *design stage* or *synthesis viewpoint* (e.g. functional or constructional) [Andreasen 1992], the space of alternatives available in a solution space, make the design process, decision intensive. In this paper, a decision is therefore assumed to exist due to a selection between a number of alternatives related to some domain [March 1994]. In the case of components, the designer encounters alternatives concerning the manipulable characteristics [Tjalve 1979]. These include reusable PDEs such as, form features, assembly features, material and surface textures (Figure 3). Similarly, the synthesis of life-phase compositional models involves the reuse of LCPEs. A decision commitment is made to *intentionally* achieve a *desired* consequence, termed the decision goal [Roozenburg et al. 1995]. Thus, alternatives are interpreted by the decision-maker, in terms of their *expected* consequences. Studies of decision making in the *real* world however suggest that decision-makers do not always know *all* the consequences of their alternatives [March 1994]. That is, decision commitments also result in *unintended* consequences.

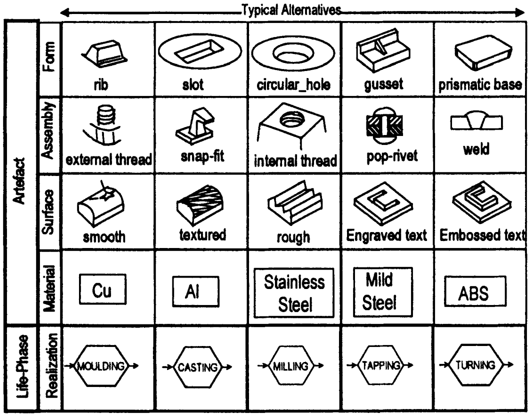

Figure 3. Some typical alternatives in mechanical artefact life design

This, highlights why *explicitly* providing designers with knowledge of unintended LCCs resulting with their commitments, is beneficial to supporting them in selecting 'life-oriented alternatives'. These commitments, made during synthesis to an evolving solution, are termed *synthesis decision commitments* [Borg 1999]. Unlike other commitments (e.g. about the design process), synthesis decision commitments are reflected in the evolving artefact's solution model (Figure 4). Through the *theory of domains* [Andreasen 1992], it can said that these commitments result in a more concrete solution if they are *concretization commitments* (e.g. committing an opening form feature) or a more detailed solution if they are *detailing commitments* (e.g. committing a value for a diameter). Since synthesis decision commitments become part of the artefact solution, then designers should be concerned with *unintended LCCs* arising from such commitments.

2.2 Implicit Co-evolution of LCC Knowledge

Figure 4 discloses a model of synthesis decision-making upon which the 'KC' approach framework to $D_sF\Sigma X$ developed in this research is based. Due to consequence arising from the *interaction* of an artefact and life-phase systems, this paper argues that life-oriented design requires that designers, concurrently generate and model the *artefact solution* and *life-phase system solutions*. These models collectively form an *artefact life model*. During such concurrent synthesis, decisions therefore concern both the *artefact model* and the different *life-phase models*.

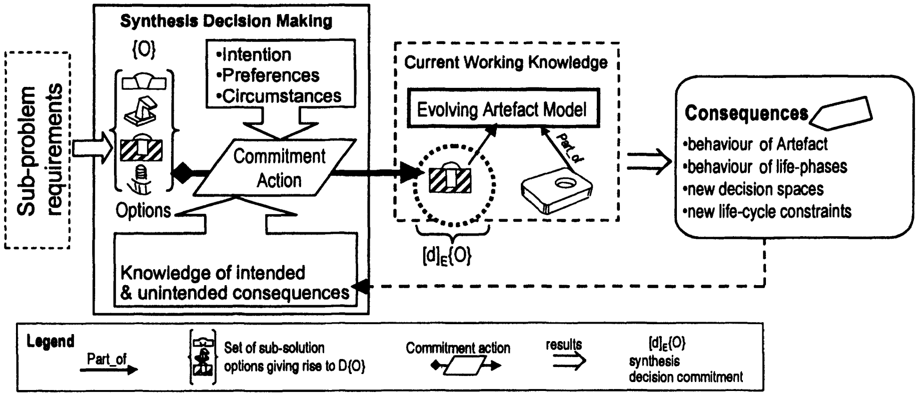

Figure 4. Synthesis decision commitment model

Basically, during synthesis, the designer *generates* a set {O} of possible solution options (that can consist of reusable PDEs or LCPEs) to the sub-problem being tackled. As an *alternative* has to be selected, the designer engages in a decision-making process (DMP). During the DMP, the designer considers *intentions*, *preferences* and known *circumstances*. Following these considerations, the designer selects an alternative by making a synthesis decision commitment $[d]_E\{O\}$ to the evolving solution model (Figure 4). The synthesis decision commitment model in Figure 4 is also applicable to life-phase system synthesis and exploration. Life-phase synthesis decisions concern for instance the selection of technical systems (e.g. milling) and system parameters (e.g. feedrate).

Founded on the theory of dispositions [Olesen 1992], research case-study observations and building upon the synthesis decision commitment model (Figure 4), a phenomena model [Borg 1999] describing *how* LCCs are generated, has been developed. This highlights that LCCs result from two fundamentally different conditions:

a) individual, *non-interacting* synthesis decision commitments, resulting in what are termed, non-interacting LCCs, i.e.$\mathbf{LCC}_{nI}$. e.g. an LCC_{ni} arising from the commitment of a pop-rivet assembly feature to bind two parts is that 'dis-assembly of the parts in the disposal phase is slow';
and

b) multiple and *interacting* synthesis decision commitments, resulting in what are termed, interacting LCCs i.e. $\mathbf{LCC}_I$. e.g. an LCC_i arising from the commitments of a hole *and* sheet-metal as a part's material is that 'a punch is required during fabrication in the realization phase'.

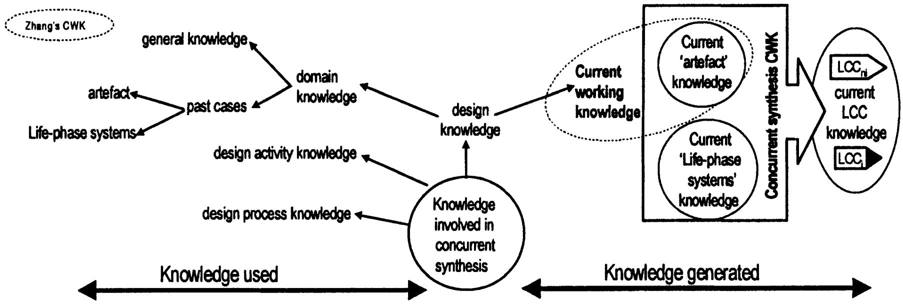

Figure 5. Implicit LCC knowledge co-evolution - modified from [Zhang 1998]

The LCC phenomena model discloses that knowledge about LCCs is *implicitly* co-evolving with *concretization* and *detailing* synthesis decision commitments being made to the artefact life solution. As Zhang [Zhang 1998] argues, design knowledge consists of *current working knowledge (CWK)* and *domain knowledge (DK)* (Figure 5). CWK is knowledge about the artefact solution on which the designer is currently working. DK is knowledge of past designs in a domain consisting of *generalized knowledge* and knowledge of specific *past design cases*. The phenomena model reflects that an expansion in the artefact's CWK is therefore caused by synthesis decision commitments. Since concurrent synthesis is a necessity if LCC_i are to be revealed during design, then in this context, the *CWK* concerns knowledge being generated of both the *artefact* and the *life-phase systems* solutions. This *Concurrent Synthesis CWK* (Figure 5) would for example also include descriptions of life-phase system composition. Hence, based on the LCC phenomena model, *implicitly* co-evolving with this *Concurrent Synthesis CWK* is knowledge of solution specific LCC_{ni} and LCC_is.

3. KNOWLEDGE INTENSIVE 'LIFE' DESIGN

Knowledge is therefore both *used* and *generated* (Figure 5) during artefact life design. If the co-evolving *LCC knowledge* is made explicit and utilized *during* synthesis decision-making, it provides *additional* knowledge that can be employed by a designer for comparing alternative PDEs and LCPEs in terms of their LCCs. This is the underlying philosophy of the *'Knowledge of life-cycle Consequences (KC)'* approach framework to $D_sF\Sigma X$. The argument is that by revealing solution specific problematic LCCs, designers can be motivated to explore alternative commitments, thereby being guided in the generation of *life-oriented* design solutions. In order to *timely* support the designer's thinking process, designers need principles disclosing how to describe evolving artefact life solutions from which current LCCs can be inferred. Further, there is a need to describe *what* needs to be captured and modelled to generate a suitable LCC knowledge base.

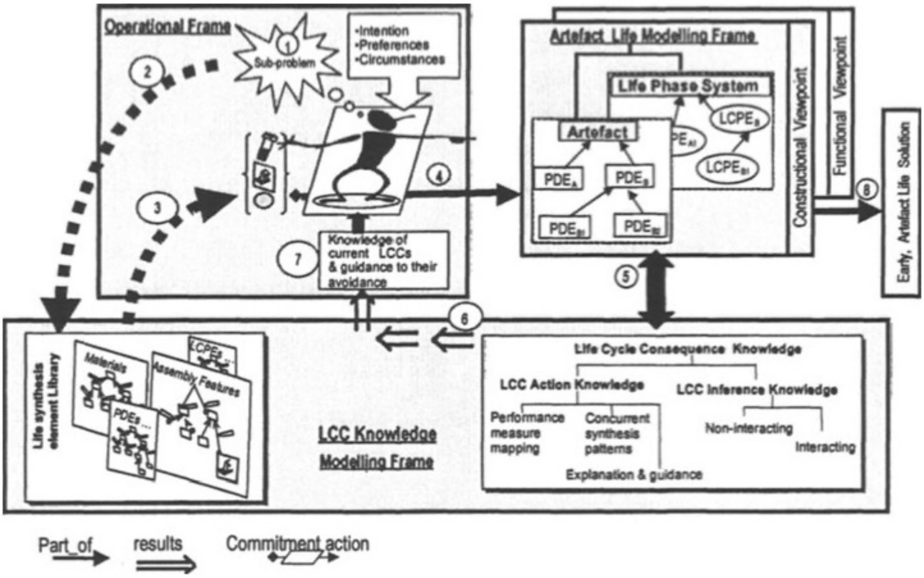

Figure 6. 'Knoweldge of Life-Cycle Consequences' Approach Framework

For this purpose, the developed $D_sF\Sigma X$ approach is based on an *Artefact Life Modelling Frame,* a *LCC Knowledge Modelling Frame* and an *Operational Frame,* these forming the *'KC' approach framework* (Figure 6).

3.1 The Artefact Life-Modelling Frame

Irrespective of the artefact / life-phase *system level* or *synthesis viewpoint,* the LCC phenomena model discloses that exploring alternative PDEs and LCPEs *implicitly* co-evolves LCC knowledge. In this respect, the *Artefact Life Modelling Frame* provides for a specific synthesis viewpoint (Figure 6), a formalism for describing an *'artefact model'* and *'life-phase system models'* that supports 'artefact life model' based LCC inference. For instance, from a constructional viewpoint, the elements describing the artefact life solution are PDEs (e.g. a hole form feature) and LCPEs (e.g. a mould core-pin). From this viewpoint, these elements are linked with *part_of* (→) relationships to form an evolving conceptual artefact model and evolving conceptual life-phase system models. These collectively form the conceptual *artefact life compositional model* (Figure 6).

3.1.1 Concept of PDE & LCPE Models

In this research, the characteristics used in defining PDE models are those that support the inference of LCC knowledge from artefact models described through PDEs. Basically, a PDE model describes reusable 'artefact system' *design characteristics*. For the component level and for synthesis from the constructional viewpoint, a PDE model could be that of a *form feature* or a *material*. PDEs which have been found relevant for designing mechanical components mainly from a constructional viewpoint are form features, assembly features, material, surface finish, dimensions and tolerances, these detailed in [Borg 1999]. Also, this research identified a number of characteristics that need to be used for modelling assembly feature PDEs as they give rise to LCC_{ni} – assembly feature joint strength, joint dynamism, integrity, joint permanence and assemby repetitivity.

Table 1 Some life-phase transformation processes & their typical characteristics

Life-phase	**[P]**	**[TS]**	**$[P]_t$**	**Od^1**	**Od^2**
Realization *(fabrication)*	Sand casting	Sand casting mould	Material solidification	Raw material	Cast component
Realization *(assembly)*	Arc welding	Welding machine	Electric power material fusion	Separate components	Bonded components
Use *(servicing)*	Grit blasting	Grid blasting device	Material abrasion	Dirty artefact surface	Clean artefact surface
Disposal	Magnetic separation	Separating machine	Magnetic attraction	Mixed components	Separated components

As with artefacts, the synthesis of a life-phase system can take place from *different viewpoints* [Mortensen et al. 1996]. LCPEs are reusable units (e.g. moulding machine) and elements (e.g. mould tool) that make up a *physical* (i.e. constructional) system delivering the *processing* effects that transform the artefact from one state to another during this interaction. Thus a life-phase $<Phase>_i$ is considerd to be composed of a set of *transformation systems* delivering *transformation process [P]* effects. The generic LCPE model developed in this research is based on Hubka & Eder's [Hubka et al. 1988] system model of a transformation process. The input *operand* Od^1 receives effects based on a *process technology* $[P]_t$ (e.g. erosion by sparks) to be transformed into *operand state* Od^2. These transformation effects are delivered through *human beings* (e.g. machining operators) and *technical systems [TS]*, the latter basically decomposable into *executing systems (e.g. tooling)* and *control systems*. As reflected by non-exhaustive examples in Table 1 derived from [Borg 1999], this model applies to processes encountered in different mechanical artefact life-phases. The LCPE characteristics that have been currently considered sufficient for supporting the inference of LCCs from the interaction of a conceptual mechanical component solution and a conceptual life-phase system solution are: *process technology, technological properties, process parameters, process parameter values, process minimum economic quantity, process technical (physical) system,* and *technical system parameters.*

3.2 The LCC Knowledge Modelling Frame

The LCC knowledge modelling frame (Figure 6) discloses *what* to *acquire*, *model* and *relate* for an application domain, together with *how* to transform and structure the established relationships into meaningful *LCC inference knowledge*. It also concerns modelling *LCC action knowledge.* The latter describes actions that arise from the detected LCCs. Further, for *relevant* LCCs to be revealed and utilized at the *right time* with both *least* and *specific* decision commitments, this frame describes how LCC knowledge can be structured using *kind_of* taxonomies, the latter also necessary for knowledge management and scaling issues. Thus, this frame, detailed in [Borg 1999] provides a *formalism* for:

a) ***a life synthesis element library:*** this consists of a structured library of various PDE and LCPE models reused within the design and life of an artefact's domain.

b) relationships between PDEs/LCPEs and LCCs describing how to model:

- <u>*LCC inference knowledge*</u>: these are descriptions *logically* relating artefact domain synthesis elements to LCC_{ni} and/or LCC_is. From the phenomena model, in the case of LCC_is, interacting relationships can be between different PDEs, different LCPEs or between PDEs and LCPEs;

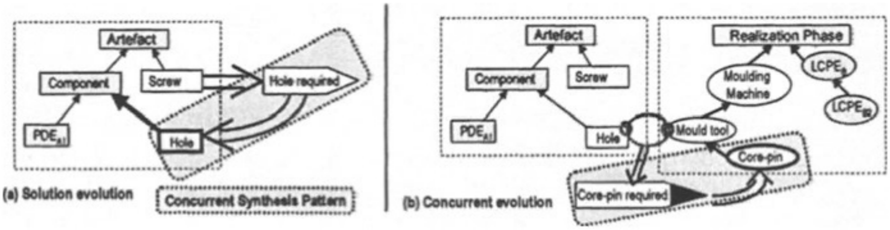

Figure 7. Typical concurrent synthesis patterns

- <u>*LCC action knowledge*</u> this describing:

concurrent synthesis patterns: in some cases, a LCC (e.g. core-pin required – Figure 7b) is a decision space 'S' with a set of decision proposals D{O} having a set of options {O}. Sometimes, the set {O} has an associated default commitments (e.g. add core-pin to mould tool). Describing such situations provides a pattern allowing commitments to be automatically made to evolve a specific <model> (e.g. machine model);

mappings between LCCs and performance measures - a LCC (e.g. sink mark) can cause a change (δ) to a *performance measure (PM)* e.g. cost, of a process [P], forming part of a *phase*. Changes in *PM* values are modelled *relative* to other possibilities (e.g. 'assembly fast) and on a range –10 to +10;

explanations of specific LCC and providing guidance to their avoidance/relaxation: Through the LCC phenomena model, knowledge of *which* commitment(s) give rise to a detected LCC can be made explicit, thus guiding designers to a list of alternative commitments that can be explored.

3.3 The Operational Frame

The Operational Frame provides:

a) a model of the $D_sF\Sigma X$ *working environment,* this composed of the human designer, who is engaged in synthesis decision making; a library consisting of a set of reusable domain specific PDEs and LCPEs; an LCC knowledge model for the domain specific elements in the library; a means by which designers can search for elements resulting in desired LCCS; a means by which designers can interact with and evolve an 'artefact life' solution model; a communication medium providing designers with (i)awareness of LCCs co-evolving with their solution description and (ii) guidance to the avoidance/relaxation of LCCs.

b) and the $D_sF\Sigma X$ *mode of operation,* this being: synthesis decision making takes place by designers as in the model of Figure 4 - commitments can be made in any order and at a *least* or *specific* commitment level; the designer is engaged in concurrent synthesis - the artefact model and the life-phase models are what the designer generates; during synthesis, designers interact with a library of PDEs and LCPEs, the latter formally described through LCC knowledge model.

Through this $D_sF\Sigma X$ *operational frame* (Figure 6), when a design sub-problem is encountered (step 1), the designer can interact with a synthesis elements library to search (step 2) for a set of suitable elements (step 3). Based on the designer's intentions, preferences and circumstances, elements are committed (step 4) to evolve the 'artefact life' model. This evolving model is monitored (step 5) by LCC inference knowledge which detects (step 6) any co-evolving LCCs. Relevant LCC action knowledge infers actions that need to be carried out, such as changes in performance measures of appropriate life-phase metrics to allow designers to monitor the artefact life behaviour. Collectively, this inferred current LCC knowledge is utilized (step 7) for exploring the avoidance/relaxation of the LCCs detected.

4. FRAMEWORK EVALUATION

The framework developed was realized as a *KICAD* prototype, 'FORESEE' for the thermoplastic component domain detailed in [Borg 1999]. As implemented, FORESEE allows designers to generate (i) an early mechanical component compositional model and (ii) a number of early life-phase system compositional models. It also provides a list of LCCs . associated with the current solution. A typical design scenario using FORESEE is presented in [Borg et al. 1998]. Key strengths and limitations of the *'KC' approach framework* have been established via FORESEE, these summarized in Table 2.

Table 2 – Summary of evaluation results - *(Legend: + Strengths & - Limitations)*

Providence Support
+ Designers become aware of multiple and interacting LCCs during component synthesis.
+ Designers made aware of company and/or life-oriented LCCs during synthesis.
Life-Oriented Synthesis Decision Making Support
+ Designers are motivated to explore a wider range of issues than originally conceived.
+ Awareness of LCC does not hinder the designer's freedom.
- Only a 'specific number' of performance measures are employed.
- The magnitude of performance measures is only useful for relative comparisons.
Practical Acceptance of Developed Means to Supporting $D_sF\Sigma X$
+ The 'KC' approach concept has been rated as useful by 91% of the evaluators.
+ A practical benefit is that it integrates synthesis with 'on-the-job' LCC training.
- Currently supports design at the component level only.
- The 'KC' approach depends on the willingness of designers to adopt new approaches/tools.
- The approach depends on the availability of a large amount of LCC knowledge.

Since 91% of the evaluators considered the approach to be useful in practice, further research is merited to address various weaknesses revealed:

(i) Artefact Life Modelling Frame Improvements - LCPE modelling needs to be extended to modelling the *environment* (eg corrosive vs non-corrosive) in which artefact and life-phase systems interact.

(ii) Knowledge Modelling Frame Improvements –The current structure (*Kind_of* taxonomies) requires research concerning the maintenance of a very large *LCC knowledge* base. Also, exploring LCCs associated with bought-in items (e.g. fasteners) furnished by *different* suppliers, requires research to generate a knowledge structure with a *customizable* perspective.

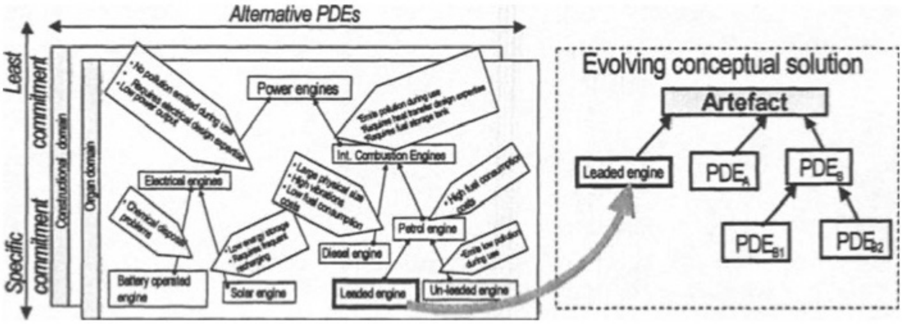

Figure 8. Example of structuring LCC_{ni} knowledge associated with organ PDEs

Research is being extended to support the reuse of synthesis elements from other synthesis viewpoints (e.g. organ) and at different artefact systems levels (e.g. sub-assembly level) (Figure 8). Research is required to *establish* and *model* LCC certainty factors and to *benchmark* the relative fluctuations in performance measures. For example on a scale of 10, should a weld line result in a fabrication cost increase of say 3 units or 8 units?

(iii) Operational Frame Improvements - As in early design, designers still resort to manual solution sketching, a challenging research goal for the operational frame is that of *knowledge intensive sketching*, whereby a hand made sketch would be monitored than used as a basis for inferrring related LCCs. This also requires work on an 'artefact life sketching language.'

(iv) FORESEE Improvements - FORESEE needs a number of improvements detailed in [Borg 1999]. For example, the knowledge manager needs to support distributed life-actors to *input* and *validate* any new LCC knowledge they encounter in the *right modelling format*.

5. CONCLUSION

As established via the FORESEE evaluation, the *'KC' approach framework* presented in this paper:

- explains *how* to model and operate a DFΣX approach for conceptual synthesis i.e. $D_sF\Sigma X$, rather than employing DFΣX *later* for candidate solution analysis;
- demonstrates that KICAD tools provide a suitable means to retain, process and explicitly *reuse* of LCC knowledge for guiding designers in 'life-oriented' design;
- reflects that the KICAD tool requirements used for FORESEE, contribute to the designer's workbench concept [Andreasen 1992];

- reflects that a set of *reusable* synthesis elements, PDEs and LCPEs are required when developing *life-oriented* KICAD tools. In this sense, PDEs and LCPEs extend *feature based 'artefact' design* to *early 'artefact life' solution design.*

However as argued, further work is required to the framework and to its realization FORESEE in order to practically exploit their utilization.

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