Exploiting Integrated 'Product' & 'Life-Phase' Features

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Abstract: Increasing competition requires more and more effort in delivering new products with better prices, good quality and environment savings. In this scenario, since most of the cost and product characteristics are dependent on commitments taken at the early design stages, designers require tools supporting them at considering the *consequences* of their decisions on the whole product life-cycle, starting from the conceptual design stage to the disposal phase. The adoption of such tools may enforce the exploration of different alternatives thus increasing the possibility of identifying the most convenient and innovative solution. Form features have been recognized as shape-oriented elements for associating geometry with engineering meaning, thus helping in reasoning on products in functional terms. However as argued in this paper, information on shape alone is insufficient for meaningful evaluation and forecast of life-cycle product consequences. The paper presents an approach for considering 'life-cycle consequences' *during* the design decision process, by taking into account both artefact features and the characteristics of the involved life-cycle systems.

Key words: Product features, Life-phase features, Life-cycle oriented design, Reuse.

1. INTRODUCTION

Design decisions can result in *unintended consequences* that have a *propagation effect* across *multiple* product life-phases such as manufacturing, use and disposal. Strong market competition and the increasing trend to environmental care are demanding major attention during product development for considering all the life-cycle issues. Thus, rather

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The original version of this chapter was revised: The copyright line was incorrect. This has been corrected. The Erratum to this chapter is available at DOI: 10.1007/978-0-387-35637-2_11

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than a *narrow* 'Design for X' (DFX) approach, designers need to adopt a 'Life-oriented Design' (LOD) approach. Such a LOD approach treats *Xs*, like life-phases (e.g. disposal) and performance measures (e.g. cost) in a *multiple* and *integrated* way during synthesis. Since it has been demonstrated that most of the product characteristics and costs depend on decisions taken at the early design stages (Andreasen et al. 1997), DFX-type knowledge should be available and used as from the conceptual design stage when the solution is still evolving. However, current manual and computer based design approaches, do not adequately support designers in handling the phenomena of propagation effects during synthesis, by *foreseeing* and exploring life-cycle consequences (LCCs) co-evolving with their *synthesis decisions* (Borg 1999). As argued in (Tomiyama 1998), for generating more added values, CAD tools must include the life-cycle knowledge. To address this situation for mechanical component life design, this paper underlines the need of tools helping designers in revealing and evaluating the consequences of their decisions simultaneously in the different environments the product will be used or manipulated, with the aim of supporting them in exploring different alternatives in order to find the best solution. In this paper, the necessity of introducing life-cycle knowledge linked to the characteristics describing products, such as form features and material is discussed. To this aim, the paper presents the concept of a life-oriented design tool employing both *artefact features* and *life-phase features*.

The paper is organized as follows. Section 2 illustrates advantages and limitations of the current use of feature technology emphasizing the need of managing additional information beyond shape. Section 3 presents a model of the decision making process and how LCCs are generated during life-oriented design, based on the consideration of the intended and unintended consequences of the chosen solution elements. Section 4 provides an overview of the developed prototype CAD system (Borg 1999) supporting designers in considering the life-cycle consequences (LCCs) co-evolving with commitments made during early design. In section 5, current limitations of the prototype and future improvements are discussed, whilst conclusions are presented in section 6.

2. CURRENT FEATURE-BASED TECHNOLOGY

The demand of supporting and utilizing engineering knowledge beyond simple geometry has resulted in the introduction of the feature concept (Cunnigan 1987, Shah 1991, Shah 1995). A feature can be seen as a reusable element, having a predictable shape and behaviour that can be associated to some engineering function or operation.

It is possible to say that, feature-based solution models provide a high level description of parts in terms of significant elements. Thus, focusing on the most important context-dependent characteristics and leaving out the basic geometric details, they support effective reasoning on the parts

Even if no argument about the importance of features exists, their real power is far from exploited. Current commercial CAD systems support the use of form features during the detail design modelling activity in terms of predefined parametric macros, corresponding to the most recurrent shapes, but no additional engineering information or consistency check on their semantic is provided. As an example consider the basic feature 'blind hole', no checks are performed to verify if during the design solution evolution it is transformed to a through hole due to some unintended interactions with added product details. This transformation can change completely the functional characteristic of the feature, e.g. from a blind cavity with only one access to a passage through which an inserted element can move through. Analogously, the attempts to automatically integrate CAD with production and analysis are still limited (Part™, FeatureWorks™, CAMWorks™) and mainly at research level (Henderson 1984, Regli 1995, Falcidieno 1989, Pinnilla 1989, Vandenbrande 1990). This is mainly due to the fact that such systems mainly focus on the geometric description of the features, and the use of fundamental information related to other solution characteristics, such as material and the available technologies, is still limited. *Figure 1* shows that even considering the same context, *e.g. manufacturing*, a feature-based description of a mechanical part can be deeply different as this also depends on the product material and the adopted technology. Thus, the same design object can be viewed in terms of two volumes to be removed if it is made of mild steel and has to be milled. Alternatively, it can be viewed to consist of a protruding rib if it requires a mould specification in case it is made from a plastic material.

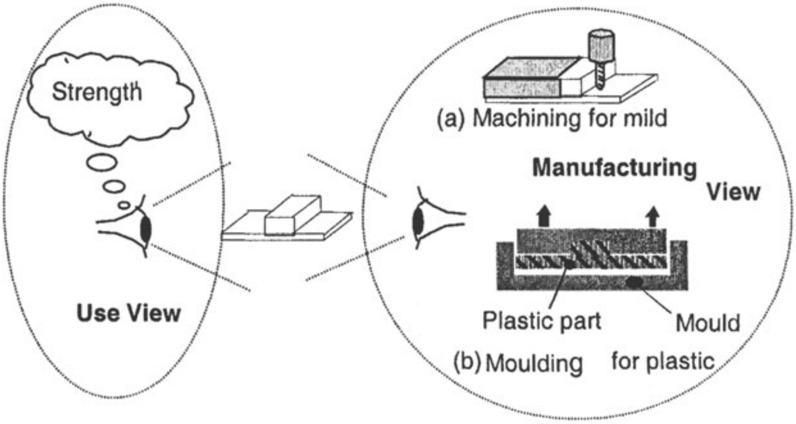


Figure 1. An example of describing the same part from different viewpoints

With the design process shifting from sequential to concurrent, the simultaneous availability of the two approaches has been required to make available the different context dependent representations to the involved experts. Thus, some activities have been focused on integrating the two approaches (Sreevalson 1990, De Martino 1994, De Kraker 1995).

At present features are mainly used during the solution synthesis activity of the detailed design stage, when details are being specified, or during the evaluation phase, when all the design commitments are almost fixed and all the fundamental decisions have been already taken. Thus changes are difficult to make and are time consuming. This is why it makes sense to consider life-cycle consequences as from early design. Some work in this area exploiting the concept of features is going on as reported (Borg 1999). However, up to now, no real support for the evolution of the design solution from the conceptual stage to the detail one is provided. Features appear to be among the key elements on which to base such an evolution (Krause 1996).

3. LIFE-CYCLE ORIENTED DESIGN DECISION MAKING

Artefact life-oriented design (LOD) implies the consideration of all the transformation activities and phenomena an artefact has to encounter right from its realization use until its disposal. To do so, it is necessary to consider the relationships among the elements describing the artefact and the involved phenomena (Otto 1998, Vajna 1997). In fact 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).* If the artefact had to interact with a *different* set and sequence of life-phase systems, different LCCs would result.

A LOD 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. 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 knowledge is *acquired* and *distributed* amongst various human actors (e.g. assembly operators, machining operators, users, servicing engineers) who are *distributed*, internally and externally to an organization. Hence, due to a lack of LCC knowledge, design decision-making takes a narrow and segmented view, this affecting the quality of the solution with respect to artefact life issues. Therefore a LOD approach requires a vast amount of distributed knowledge to be acquired, readily available and easy to access in order for it to be explicitly utilized during *synthesis*. Understanding the phenomena of how LCCs are generated and propagated during *synthesis decision-making* is thus essential for the development of CAD tools supporting LOD.

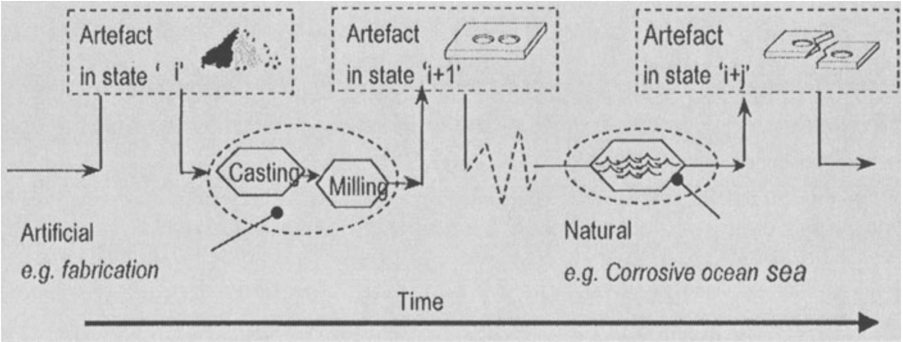


Figure 2. Interactions between artefact and life-phase systems

3.1 'Artefact Life' design decision-making

A mechanical artefact can be considered as a decomposable system (Hubka. 1988) consisting of a number of *re-usable* elements, e.g. sub-assemblies, composed in turn of simpler elements such as form features, assembly features, material and surface textures. All these elements, termed in this paper as *Product Design Elements (PDEs*), are related to each other with *'part of'* relationships. Similarly, the life-phases (e.g. *design,* *realization, use, 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. Models of these systems (e.g. milling machine) can be also decomposed into sub-systems (e.g. a work piece holding device), these termed *Life-Cycle Phase Elements (LCPE).* Such a decomposition supports life-phase system compositional modelling, where *LCPEs* are *related* to *'part of'* relationships.

The design process can be seen as a decision intensive activity, which involves the simultaneous specification of the artefact (i.e. using relevant PDEs) and the technical systems involved in the different life-phases (i.e. using relevant LCPEs). Regarding the artefact, irrespective of the specific *design stage* (e.g. conceptual vs. detail) or *synthesis viewpoint* (e.g. functional or constructional), the decision maker has to make a choice between a numbers of alternatives related to the domain (March 1994). In the case of components, the alternatives concern a number of manipulable characteristics (Tjalve 1979), which include reusable PDEs. Similarly, the synthesis of life-phase compositional models involves the reuse of LCPEs. In *Figure 3*, some examples of typical alternatives in mechanical design are shown.

The alternative selected, termed here the decision commitment, is a result of the synthesis decision-making process. A decision 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. Designers, as human beings, are known to have limitations concerning knowledge possession and processing. 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).

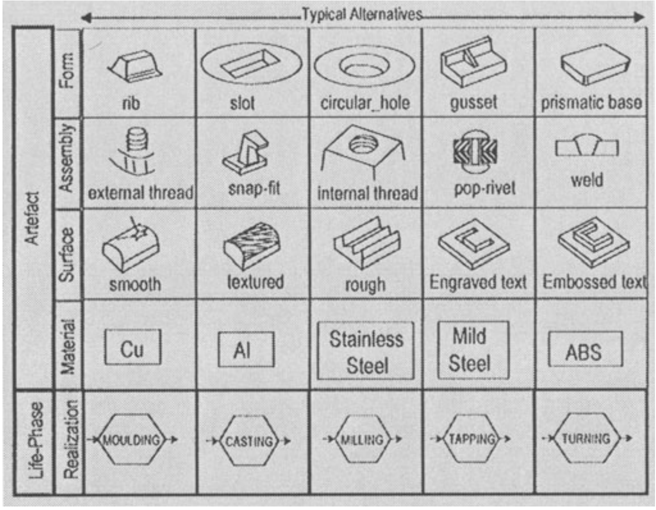


Figure 3. Some typical alternatives in mechanical artefact life design

Unlike other commitments (e.g. about the design process), synthesis decision commitments are directly reflected in the evolving artefact's solution model (*Figure 4*).

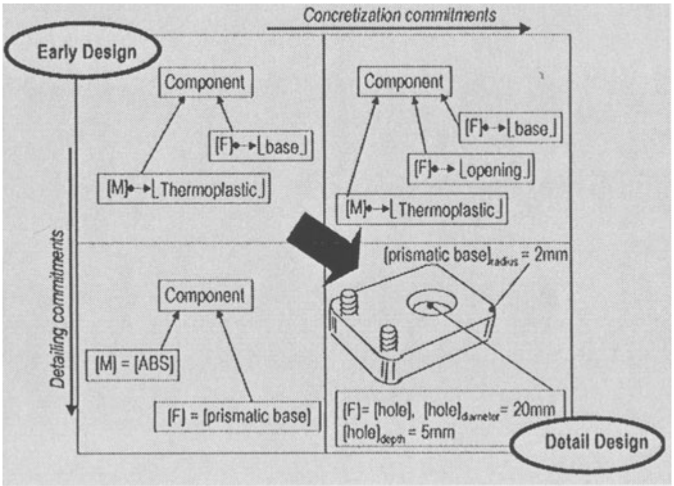


Figure 4. Artefact model evolution with synthesis decision commitments

Through the *theory of domains* (Andreasen 1992), it can be said that these commitments result in a more concrete solution if they are *concretisation 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. Modelling these phenomena is useful for this research.

3.2 A synthesis decision commitment model

Figure 4 discloses a model of synthesis decision-making upon which the approach framework to LOD developed in this research is based. Due to consequences 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*. Without concurrent synthesis, consequences arising from the interaction of specific artefact solutions and specific life-phase systems would be difficult to cater for. This need can be explained via the example in *Figure 1*. Depending on the material defined for the part, different processing technologies are required during the manufacturing phase. This introduces *different* consequences that can in their turn affect the product specification. For instance, to obtain a feasible part solution, constraints related to the machining have to be considered, such as the minimum width of the rib to avoid cracks/spring effects during the milling operation. Alternatively, shape modifications may be necessary (e.g. introduction of draft angles) due to the sticking effect if the plastic part is to be efficiently ejected from the mould.

Therefore, for this research purposes, from a generic point of view, this decision making process can be described as follows. Basically, during synthesis, the designer *generates* a set {O} of possible solution options to the sub-problem being tackled. For example for the sub-problem *how can two parts be joined together?* the set of solution options {O}may be {fasteners or adhesive or snap-fits}. Thus, in the case of routine and innovative design, the set of options {O} consists of reusable PDEs or LCPEs. As an *alternative* has to be selected from the set of options available, the designer engages in a decision-making process (DMP) to make a selection. 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 5*). The synthesis decision commitment model in *Figure 5* is also applicable to life-phase system synthesis and exploration. In the latter case, the solution model being generated and explored is that of a life-phase system and the decision-making process concerns feasible, alternative LCPEs (e.g. alternative fabrication systems). Life-phase synthesis decisions concern for instance the selection of technical systems (e.g. milling) and system parameters (e.g. a feed-rate value). In order to develop a tool supporting designers in foreseeing LCCs evolving with their commitments, it is therefore important to understand how LCCs are generated.

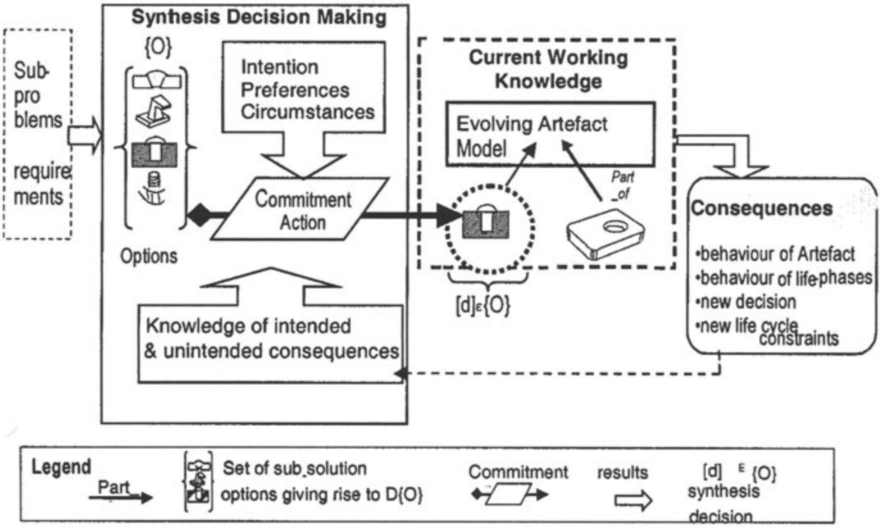


Figure 5. Synthesis decision commitment model

3.3 Life-cycle consequences generation

Based on the foregoing arguments, it can be noted that LCCs result from two fundamentally different conditions:

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

ii. multiple and *interacting* synthesis decision commitments, resulting in what are termed, interacting LCCs i.e. **LCC$_i$**. For example, an LCC$_i$ resulting from the commitment of a hole *and* the commitment of sheet-metal as a part's material is that 'a suitable punch needs to be used during fabrication in the realization phase'.

Moreover, the knowledge about LCCs is *implicitly* co-evolving with *concretisation* and *detailing* synthesis decision commitments being made to the artefact life solution. In fact, it is possible to say that whilst the set of possible solutions reduces with the *detailing* and *concretisation* of the commitments made, in the meantime, the determination of the LCCs becomes more certain and covering more situations. Some LCC can be deduced at the conceptual stage, e.g. for a plastic part, a mould has to be defined, while most of them can only be deduced precisely during the detailing stage. This concerns mainly the case of consequences related to dimensional and positional values that give rise to specific feature interactions both within the artefact and among the artefact and life-phase system. Examples of such interactions are shown in *Figure 6*. In *Figure 6*(a), the concretisation commitments for the two PDEs (pocket features) give rise to a thin separating wall, which under specific LCPEs conditions can produce an unintended crack. Similarly, *Figure 6*(b) demonstrates that concretisation commitments of two holes (PDEs) to be generated via a punch press (an LCPE) have to be checked against the LCPE features in order to avoid unintended LCCs, such as the interference among the punching tool holders.

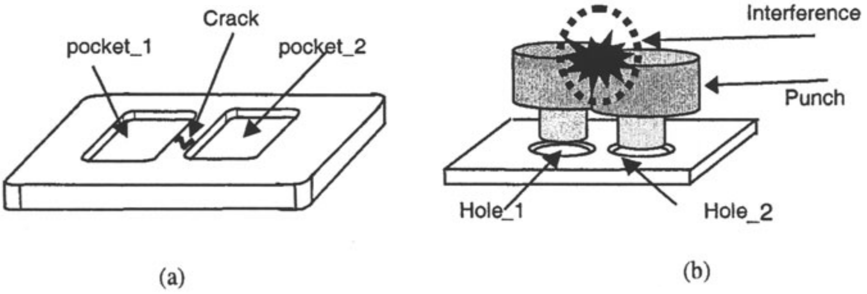


Figure 6. Examples of interactions giving rise to unintended LCCs: (a) interaction of PDE-PDEs features (b) interaction of PDE - LCPE features

4. TOWARDS FEATURE-BASED COMPONENT 'LIFE ORIENTED' DESIGN TOOLS

The phenomenon of co-evolving LCCs therefore discloses that *during* artefact life design, knowledge is both *used* and *generated.* If the co-evolving *LCC knowledge* is explicitly revealed and utilized *during* synthesis decision-making, it provides *additional* knowledge that can be employed by designers for comparing alternative PDEs / LCPEs in terms of their resultant LCCs. If made aware of unintended consequences, a designer may therefore retract a synthesis commitment to explore other alternatives. 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 co-evolving LCCs can be inferred. Further, to adopt this approach, there is a need to describe *what* needs to be captured and modelled to generate a suitable LCC knowledge base. Therefore, based on the decision commitment model (*Figure 5*),'Knowledge *of life-cycle Consequences' (KC)* approach framework has been developed, this composed of an *artefact life modelling frame*, a *knowledge-modelling frame* and an *operational frame.*

4.1 Artefact life modelling frame

In this approach, an 'artefact life' solution is described in terms of an 'artefact model' and related 'life-phase system models', these models described via reusable PDE and LCPE models respectively. Basically, a PDE model describes reusable 'artefact system' *design elements*. For instance, for component synthesis from a constructional viewpoint, typical PDE models are those of form *features* or of materials. PDEs that have been found relevant for designing mechanical components from a constructional viewpoint are *form features, assembly features, material, surface finish, dimensions* and *tolerances*, these detailed in (Borg 1999). For example, this research identified a number of characteristics that need to be used for describing assembly feature PDEs as they give rise to LCC_{ni} – *assembly feature joint strength, joint dynamism, integrity, joint permanence* and *assembly repetitivity.*

For 'life-phase system modelling', designers are concerned with manipulating reusable life-phase system elements. As with artefacts, the synthesis of a life-phase system models can take place from different viewpoints. Thus a life-phase model $<Phase>_i$ is considered in this paper to be composed of a set of *transformation systems* (from a constructional viewpoint) delivering *transformation process [P]* effects. For instance, a fabrication system (see *Figure 2*) can be composed into a casting process followed by a milling process. LCPEs are thus reusable units (e.g. milling machine) and sub-elements (e.g. workpiece fixture) that make up a transformation system delivering the *processing* effects that transform the artefact from one state to another during this interaction. 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 transformation processes encountered in different artefact life-phases.

As explained in (Borg 1999), LCPE characteristics that have been considered sufficient for describing LCPE models 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.* As the current focus has been on supporting early design, certain characteristics have been omitted from this LCPE model e.g. the material of the elements making up a [TS], the human operator (e.g. a novice *versus* an experienced machining operator), the assembly features used in a [TS], the control system of a [TS] and the environment (e.g. humid) in which the [TS] operates.

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

Life-phase	*[P]*	*[TS]*	*$[P]_t$*	*Od^1*	*Od^2*
Realization (fabrication)	*Spark Erosion*	*Spark eroder*	*Material erosion by electric sparks*	*Initial component form*	*Different components form*
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 (maintenance)	*Grit blasting*	*Grid blasting device*	*Chip formation by material abrasion*	*Dirty artefact surface*	*Clean artefact surface*
Disposal	*Magn. separation*	*Separating machine*	*Magnetic attraction*	*Mixed components*	*Separated components*

4.2 LCC knowledge modelling frame

This frame concerns the formalization and definition of the following:

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. Elements in the library can be generic (e.g. a hole form feature) or domain specific (e.g. mould core-pin). This library extends the designer's mental knowledge base with reusable synthesis elements used for generating 'artefact life' solutions.

b) ***relationships*** between PDEs/LCPEs and associated LCCs describing :

   i. LCC inference knowledge: this consists of descriptions *logically* relating artefact domain synthesis elements to LCC_{ni} and/or LCC_is. Based on the phenomena model, in the case of LCC_is, interacting relationships can be between different PDEs, different LCPEs or between PDEs and LCPEs;

   ii. LCC action knowledge describing:
      - *concurrent synthesis patterns:* these correspond to default commitments(e.g. add core-pin to mould tool) associated with certain LCCs (e.g. core-pin required *Figure* 7–b) that allow the automatic evolution of a specific model (e.g. moulding machine model
      - *mappings between LCCs and performance measures* – a LCC (e.g. sink mark) can cause a change to a *performance measure* (e.g. cost), of a technical process [P] (e.g. moulding), forming part of a phase (e.g. realization). Changes in performance measure values are modelled *relative* to values resulting from other possibilities, e.g. on a range –10 to +10.
      - *explanations of specific LCC and guidance to their avoidance/relaxation*: having inferred a LCC (e.g. a weld line defect), designers need explanation of what the LCC means and what it effects, together with guidance to its 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 the list of alternative commitments that can be explored.

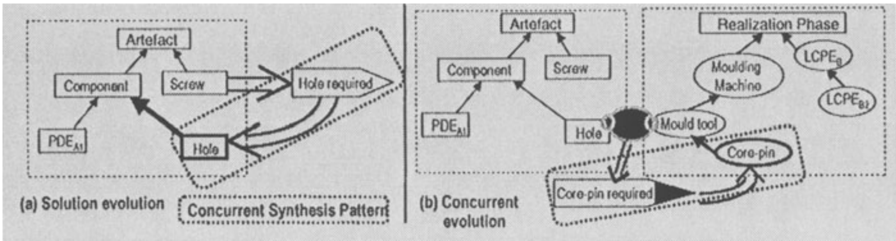


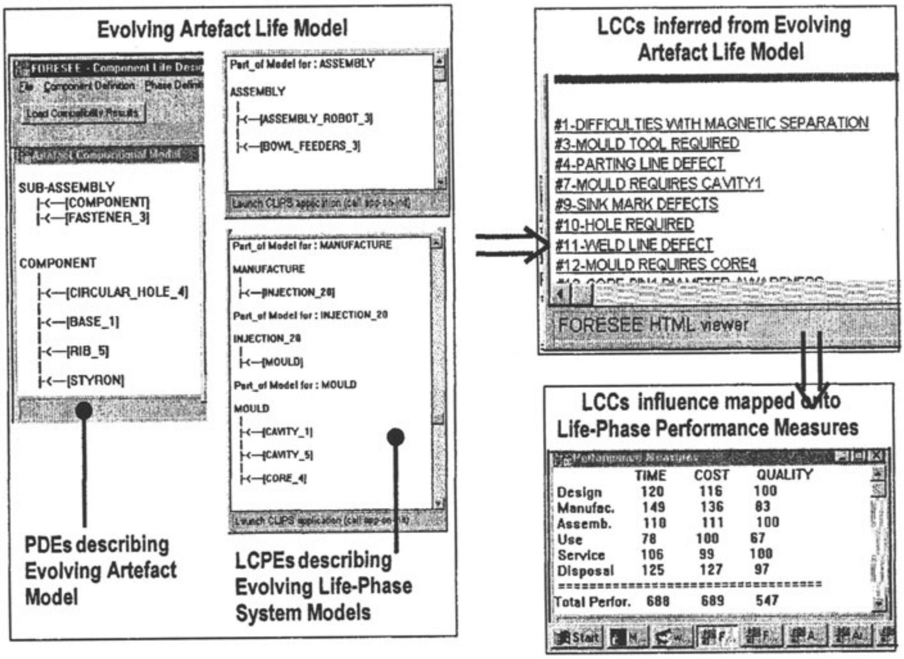
Figure 7. Typical concurrent synthesis patterns

4.3 Operational Frame

The operational frame provides a LOD *working environment* and *mode of operation.* Basically, through this frame and the other frames in the 'KC' approach framework, 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* that 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 co-evolving LCC knowledge is utilized (step 7) for exploring the avoidance/relaxation of the detected LCCs.

4.4 Prototype CAD System

The 'KC' approach framework described has been implemented as a prototype CAD system, named FORESEE. As implemented, it allows designers to generate and describe (i) an early mechanical component compositional model and (ii) a number of early life-phase system compositional models. It reveals a list of LCCs associated with the current solution state and an associated set of *multi-X* relative performance measure values to proactively guide the designer to monitor the performance of the evolving artefact life solution. FORESEE also provides explanations of detected LCCs and guidance to their avoidance. Further, a history of the decision commitments made and their associated impact on performance measures is provided. The system details and a typical design scenario of its use are presented in (Borg et al. 1998). In *Figure 8*, some snapshots of the developed prototype are shown.



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SUB-ASSEMBLY
   |-<--[COMPONENT]
   |-<--[FASTENER_3]

COMPONENT
   |
   |-<--[CIRCULAR_HOLE_4]
   |
   |-<--[BASE_1]
   |
   |-<--[RIB_5]
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   |-<--[STYRON]
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Part_of Model for : ASSEMBLY

ASSEMBLY
 |
 |-<--[ASSEMBLY_ROBOT_3]
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 |-<--[BOWL_FEEDERS_3]
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Part_of Model for : MANUFACTURE
MANUFACTURE
 |
 |-<--[INJECTION_20]
Part_of Model for : INJECTION_20
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 |-<--[MOULD]
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MOULD
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 |-<--[CAVITY_1]
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 |-<--[CAVITY_5]
 |
 |-<--[CORE_4]
```

#1-DIFFICULTIES WITH MAGNETIC SEPARATION
#3-MOULD TOOL REQUIRED
#4-PARTING LINE DEFECT
#7-MOULD REQUIRES CAVITY1
#9-SINK MARK DEFECTS
#10-HOLE REQUIRED
#11-WELD LINE DEFECT
#12-MOULD REQUIRES CORE4

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              TIME     COST     QUALITY
Design        120      116      100
Manufac.      149      136      83
Assemb.       110      111      100
Use           78       100      67
Service       106      99       100
Disposal      125      127      97
==================================
Total Perfor. 688      689      547
```

Figure 8. Sample screen shots of the prototype tool FORESEE

5. PROTOTYPE TOOL EVALUATION AND FUTURE EXTENSIONS

The implementation demonstrated that the knowledge intensive 'KC' approach framework can be realized using existing computer technology. Via the FORESEE prototype and an empirical evaluation, strengths and limitations of this approach have been established (Borg 1999). Since 91% of the evaluators considered the integrated 'product' and 'life-phase' feature-based LOD approach to be useful in practice, further research is merited to address the revealed weaknesses such as:

(i) Feature-based LOD approach improvements

The current approach provides the user with general LCC which depend on specific PDEs and LPEs assumptions. What would be interesting is the possibility of evaluating a solution generated in terms of PDEs associated with alternative LCPEs e.g. to evaluate the LCCs that result from changing the producer, and consequently the system (i.e. LCPEs), for that specific component. Also required is support for the evolution of the component solution in terms of PDEs and in particular feature instantiation since, as argued in section 3.3, their interactions strongly effects the detected LCCs. This means that algorithms for the recognition of feature interactions should be applied, and if the case, to re-organize the description to check if the previously obtained LCCs are still valid, or if new ones have been generated.

(iv) FORESEE Prototype System Improvements
For practical purposes, FORESEE also needs improvements. For example, the knowledge management facility needs to be extended to support distributed life-actors to *input* any new LCC knowledge they encounter in the *right modelling format* and in *validating* the input knowledge. Work is also required to enable FORESEE to simultaneously handle and display *multiple* artefact life solutions for easier comparison purposes.

6. CONCLUSION

This paper presented an integrated 'product feature' and 'life-phase feature' *based* approach for supporting 'component life design'. Its implementation, the FORESEE prototype, discloses that the approach contributes a step towards the development of *Knowledge Intensive CAD* (KICAD) tools aimed at pro-actively supporting designers in generating 'life-oriented' artefact solutions. As established, the approach concept:

- reflects that a set of *reusable* synthesis elements i.e. PDEs to describe 'artefact models' and LCPEs for describing 'life-phase system models' 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*;
- demonstrates that KICAD tools provide a suitable means to retain, process and explicitly *reuse* captured LCC knowledge for guiding designers in LOD;
- reflects that the general system requirements on which the FORESEE prototype is based, contribute to the development of LOD tools;

As discussed, further work is however required to this knowledge intensive feature-based approach to LOD if it is to practically support the design process as from its early conceptual stage to the detailed stage. As a first step, this requires the specification of models able to represent reusable elements such as geometry and material in a vague way, together with the development of algorithms for feature interaction recognition and mapping from such incomplete solution descriptions.

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