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INTEGRATED PRODUCT DEVELOPMENT BASED ON FORESEEING LIFE-CYCLE CONSEQUENCES

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Abstract: During product development, there is a *phenomena* that is continuously present, whether stakeholders are aware of it or not. This phenomena concerns the generation of Life-Cycle Consequences (LCCs) with design decision commitments. The understanding of this phenomena and how consequences are generated has been exploited to develop the 'Knowledge of Life Cycle Consequences' Approach. Evaluations performed via a number of computational prototypes based on this approach have repeatedly concluded that this approach allows designers to foresee consequences spanning multiple life phases. This approach thus promotes *Design Synthesis for Multi-X,* which is fundamentally different from an approach using multiple, standalone DFX methods. Thus the approach developed contributes a means of how to achieve integrated product development.

Keywords: *Mechanical Design, DFX, Computer Aided Design, Product Development Metrics*

1. INTRODUCTION

Industry is under increasing pressure to deliver products that cater for a host of total life-cycle requirements [1]. At the same time, the research reported in this paper highlights a neglected *phenomena* taking place during product development. A *phenomena* is similar to gravity: whether one knows about it, whether one is young or old, whether one understands how it operates, gravity is continuously acting upon us. Similarly, the *phenomena* addressed in this paper is continuously present during product development whether one is aware of it or not. This phenomena, called Life-Cycle Consequences (LCCs) is that 'Design phase decisions have consequences that propagate across different Product Life-Phases'.

Several cases of this phenomena have been documented by BORG [2]. Consider for instance the case when a designer *(Figure 1)* of say a thermoplastic part is during design synthesis, making the decision commitment to use a fastener such as a bolt, to assemble this part to a complex mechatronic system. The good intention of the designer was in this case to achieve easy dis-assembly (in the future servicing phase) unlike for instance using ultrasonic bonding. However, this commitment has a consequence that a hole of diameter ømm is required in this thermoplastic part. In addition, this commitment will now result in a consequence that the mould tool for mass producing the plastic part must requires a core pin, whose diameter must

take into consideration the hole diameter required as well as the shrinkage factor of the plastic to be used. The presence of the core pin will now give rise to a new consequence i.e. that weld line defects during will be potentially formed during the manufacturing phase. The weld line defects will in turn have a consequence on the part's structural integrity during the use phase that can result in more scrap.

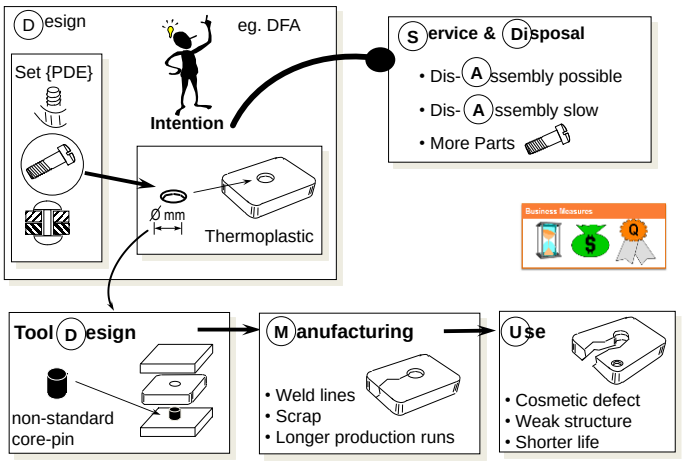


Figure 1. LCC phenomena: design decisions progagate across the whole life

From case-study observations, a phenomena model [2] describing how life cycle consequences [LCC] are generated from synthesis decision commitments made under two different conditions has been generated, this schematically illustrated in *Figure 2.*

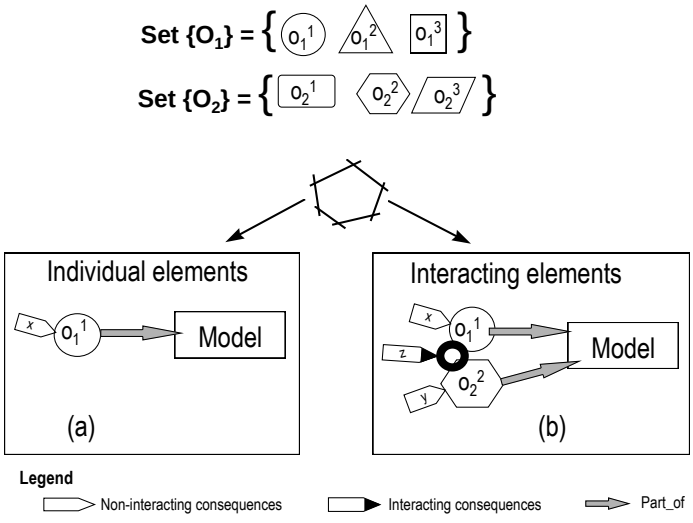


Figure 2. LCC phenomena model: interacting and non-interacting commitments

- **Non-Interacting LCC*ni***: Consequences in this case result during an artefacts's life due to the presence of individual artefact design elements (e.g. a hole feature) or life-phase elements (e.g. a mould tool) introduced by synthesis decision commitments made independent of other synthesis elements present in the artefact life model.
- **Interacting LCC*i*:** Consequences in this case depend on a set of 'n' life synthesis commitments where n > 1.

These LCCs and the phenomena model established, indicate that there is a need of means by which LCCs can be foreseen and catered for. Otherwise, the consequences impacting the different life phases will negatively influence the performance of product development.

2. MEANS FOR HANDLING THIS 'LCC PHENOMENA'

A review by BORG and YAN [3] had established that approaches like team based [4], DFX [5][6], knowledge based [7], constraint based [8] and failure mode and effects analysis (FMEA) [9] are limited to supporting 'life-oriented' design synthesis so necessary for achieving integrated product development. Although team working brings all expertise together, it does not ensure that knowledge supporting design decision making is available continuously as team members are often working alone (see *Figure 3*), still making decisions in the interim period between design review meetings.

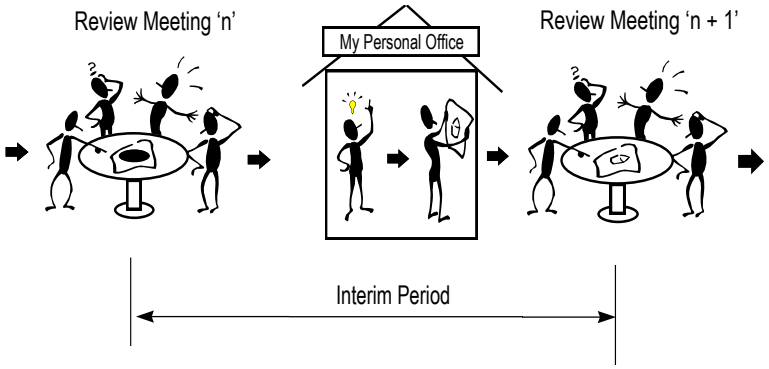


Figure 3. LCC: Decisions being taken in the interim period between team meetings

Thus, due to the phenomena of LCCs, interim period decision result in conseqeunces on the an artefact's life. Teams also have difficulties in recognizing the complex propagation effect of design decisions.

In "Design for X", a major drawback is that DFX knowledge tends to be segmented by artefact life-phase aspect (e.g. Design for Manufacture versus Design for Service). In addition DFX knowledge is employed late, for candidate solution analysis when major design decisions have already been committed. Further, DFX

knowledge is generic as it does not consider the actual resources that will be encountered by the artefact being design.

Knowledge-based (KB) design tools provide predictive modelling power with the breadth of life-phase expertise. However, this predictive power, is generally being employed for candidate solution analysis after design decisions committed. In addition, KB tools can only provide a narrow and segmented view of a candidate solution as knowledge captured tends to be of single life-phase view, making it difficult to explore trade-offs between multiple life-cycle aspects of an evolving design solution. A constraint network (CN) based approach requires a pre-defined network of parameter relationships describing the conceptual solution itself. This means that CNs provide support late in the design process. Further, their non-directional inference capability, whilst useful to supporting the cooperation between multiple perspectives, distorts the way designers work in reality because it results in a modelling world where there is no distinction between design characteristics that can be defined in reality by the designer and properties that are derived such as costs.

With *Failure Modes and Effects Analysis (FMEA)*, failure modes, mostly of the use phase, are identified late and subject to the analyst's design solution interpretation. Thus these different approaches exhibit one or more of the following limitations:

- they provide an insight into LCCs late in the design process;
- they provide a narrow and segmented insight into consequences being generated;
- they provide a generic insight rather than problem/company specific providence;

These limitations suggest that any *means* allowing designers, to have an early insight into LCCs influencing a number of life-phases, is highly desirable if Integrated Product Development is to be truly achieved.

3. A KNOWLEDGE OF LCCS APPROACH TO HANDLING PHENOMENA

Thus based on the identified phenomena of life cycle consequences (LCC) and the lack of available support means, this research embarked on developing a design approach concept aimed at exploiting relevant knowledge of LCC to help foster *Design Synthesis For Multi-X* which is core for truly achieving an Integrated Product Development Approach. The established phenomena model highlights that for generating a life-oriented design solution, *concurrent synthesis* of the 'artefact' and 'life-phase system' is a necessity if designers are to do 'Design Synthesis for Multi-X'. Otherwise, solution specific LCC_i will be difficult to reveal and cater for during synthesis. This understanding provides the basis to *what* should be captured and modelled to causally relate synthesis decision commitments and life cycle consequences. This understanding can therefore be exploited for:

- *foreseeing LCCs:* depending on commitments made, modelled LCCs co-evolving with the solution, can be revealed during synthesis to predict the influence on the measurements of life cycle performance;
- *solution synthesis guidance:* it provides a means to search for elements that need to be committed to result in an intended consequence; e.g. what PDEs result in a sub-assembly that is easy to dis-assemble in the disposal phase?
- *consequence avoidance/relaxation:* designers can be pro-actively made aware of consequences and their *source* commitments; this knowledge provides guidance to *what* specific commitments can be *explored* to avoid/relax a consequence revealed.

Using these foundations, the *'Knowledge of life-cycle Consequences (KC)'* approach framework to 'Design Synthesis for Multi-X' has been developed, based on the following three frames [2].

- *Operational frame:* this concerns the operating principles of the approach. Basically, it assumes that many well-developed solution concepts (PDEs) and well-known life cycle phase elements (LCPEs) are *re-used* during synthesis and encountered during the total life of an artefact. A fundamental operating principle of the approach is that a designer is engaged in concurrent synthesis – the *artefact life model* (consists of *artefact model* and *life-phase system models*) is *what* the designer generates during component life design synthesis. Essentially the approach supports a designer in making life-oriented synthesis decision commitments, by pro-actively and timely revealing LCCs co-evolving with a commitment. This awareness allows a designer to therefore foresee and take actions on artefact life-cycle consequences revealed. For this purpose, when a design sub-problem is encountered (step 1), the designer interacts (step 2) with a synthesis elements library to search for a set of suitable elements (step 3). Based on known *intentions*, *preferences* and *circumstances*, the designer commits (step 4) an element to evolve the artefact life model.
  This evolving model is monitored (step 5) by *LCC inference knowledge* which reveals (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 knowledge is utilized by the designer (step 7) for exploring the avoidance/relaxation of the LCCs detected and for the handling of trade-off between conflicting LCCs associated with the evolving solution.

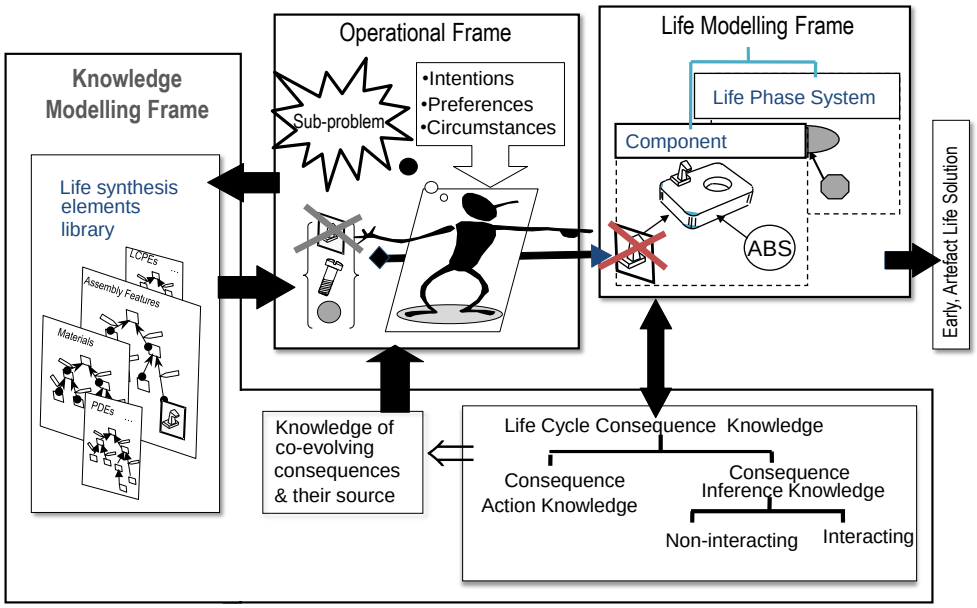


Figure 4. Established KC Approach Framework for handling LCCs

- *Artefact life modelling frame:* due to the need of concurrent synthesis, designers need to handle both artefact and life-phase system models. This frame therefore comprises a set of domain specific *synthesis elements* (PDEs and LCPEs) linked with *part_of relationships* describing the evolving compositional *artefact* and *life-phase system* models for a pre-set synthesis viewpoint, in this case from a constructional perspective;
- *Knowledge modelling frame:* This concerns the description of:
  - a synthesis element library, consisting of various models of synthesis elements (PDEs and LCPEs) reused within the design and life of a mechanical artefact domain. In the case of components, this includes models of form features, assembly features, and materials and LCPEs such as fabrication systems and assembly systems;
  - life-cycle consequence knowledge, consisting of:
    - LCC inference knowledge for revealing non-interacting and interacting LCCs co-evolving with synthesis decision commitments;
    - LCC action knowledge, for performing actions specific to a consequence inferred, this including LCC to performance mapping, concurrent synthesis patterns and guidance/explanation to LCC avoidance/relaxation.

4. EVALUATION OF THE 'KC' APPROACH FRAMEWORK

To evaluate the exploitation of the LCC phenomena model, the 'KC' approach framework has been implemented and adopted over the years in a number of prototype computational tools for a range of engineering applications including (i) thermo-

plastic parts [10] (ii) biomedical devices [11] (iii) collaborative design scenarios [12] (iv) intelligent sketching [13] (v) factory design [14] and (vi) emotional based product development [15].

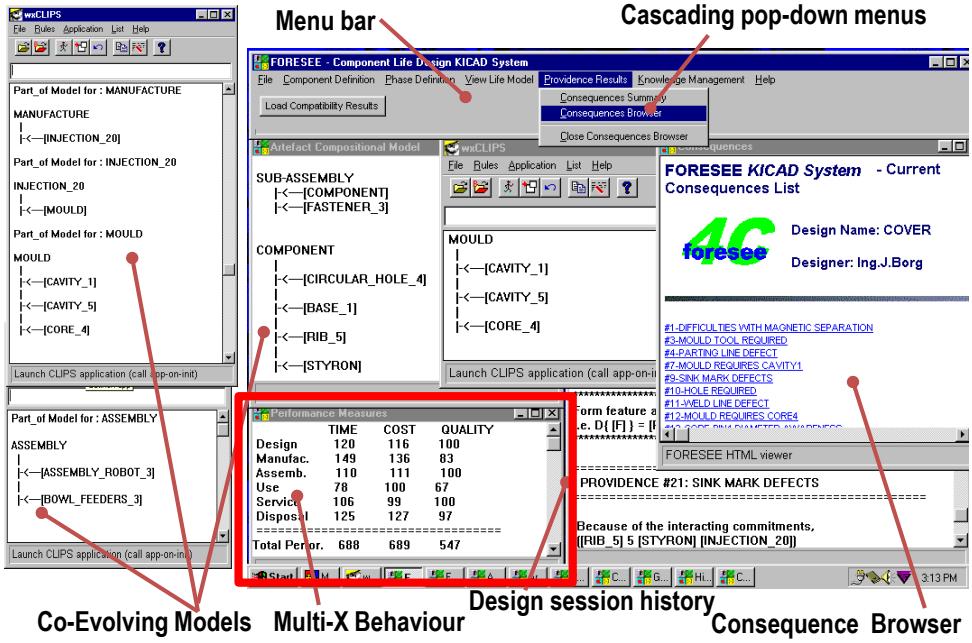


Figure 5. Screenshot of the FORESEE [2] Prototype System User Interface

For instance, the FORESEE system *(Figure 5)* developed for plastic part design was implemented as a Knowledge Intensive CAD (KICAD) employing a LCC knowledge model and implemented in a Windows environment using CLIPS [16]. For handling interacting commitments, FORESEE employed frame-based reasoning [17], this useful for modelling causality between interacting elements belonging to different abstraction levels in a *kind_of* taxonomy and life-cycle consequences. As illustrated in *Figure 5*, designers can see the impact of their decision commitments on a number of performance metrics in different life-phases via the *'Multi-X Behaviour'* window. In addition, designers can see the reasons for the generated LCCs as well as be guided on how to avoid/relax them through the *Consequence Browser.*

The various prototype implementations have established a number of strengths and weaknesses of the KC approach framework, namely that it:

- Proactively supports foreseeing of LCCs, across multiple phases, during solution synthesis and with least/specific commitments
- Raises awareness of consequences propagating across different life-phases helps influence the designer's thinking patterns;

- Motivates designers to ‘explore’ total life opportunities, avoid/relax detected LCCs;
- Assists in the conscious commitments of artefact life-phase system decisions;
- Supports the reuse of ‘artefact life’ scenarios;
- Integrates the activity of design synthesis with learning;
- however depends on the acquisition, addition and validation of a vast amount of LCC knowledge to be useful in practice;

5. CONCLUSION

The computational ‘KC’ approach framework presented in this paper *integrates* the activity of solution synthesis with the activity of foreseeing the artefact life behaviour. This integration makes the approach *fundamentally* different from *first generating* a solution and *later* analysing the candidate solution for conflicts with artefact life issues. It has been achieved by monitoring the fluctuation of various life-cycle performance measures. The positive evaluation of this approach through a number of different research projects at the University of Malta highlights that LCC knowledge plays a significant role in supporting designers to explore decisions’ influences on multiple life-cycle metrics such as cost, tiem and quality. In addition, the author reports that the underlying phoneomena of LCCs has been very relevant in technical consultancy work performed for industry, as it helped untangle a number of mysterious causes to problematic issues faced during product development.

To concolude, capturing and codifying such LCC knowledge is therefore beneficial for developing intelligent digital design tools that proactively aid designers generate life-oriented design solutions. Thus, the *Knowledge of life-cycle Consequences* approach framework contributes a significant step towards the realization of $D_sF\Sigma X$ which is core to achieving *Integrated Product Development*.

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