NordDesign 2006
August 16 – 18, 2006
Reykjavik, Iceland

Towards uncertainty-aware management of design reuse

Cristian Nilsson, PhD-student

Dept of Engineering Design and Materials
Norwegian University of Science and Technology, Trondheim
cristian.nilsson@ntnu.no

Abstract
This paper explores possible approaches to design reuse in the context of multi-product developing companies. As a background, the main differences between design sharing across concurrent products and design reuse over time are highlighted. Then, design reuse is analysed around three main enablers of reuse: the willingness to reuse (business and socio-cognitive view), the availability of suitable solutions to reuse (artefact view), and the means to transfer design solutions for reuse (process/tools view). It is argued that many potential benefits of design reuse cannot be exploited unless proactive efforts are invested to facilitate future reuse, and that the choice of appropriate proactive reuse approach is shaped by the *predictability* of future reuse needs. Three conceptually different types of reuse approaches are presented, according to the commitment and timing of the decision to reuse (in advance or case-by-case): ad-hoc reuse, planned reuse and option-based reuse approaches. Finally, managerial implications for an uncertainty-aware reuse approach are discussed.

Keywords: design reuse, multi-product development, reuse strategies

Introduction

Why reuse design solutions?
In relation to product design at multi-product developing companies, reuse in a broad sense is very common, because engineers tend to learn and share knowledge that in one or another way becomes reflected in the chosen solutions. Through reuse of design experiences, synergies are thus exploited between subsequent products. Here, we are especially interested in a narrower aspect of design reuse, namely the *deliberate* choice to reuse a past design solution instead of designing a new solution. The expected benefit when reusing design solutions is usually sought in the *avoidance* of the life cycle costs of new solutions [1][16], especially in relation to

1) Product development, through avoided designing and testing, potentially freeing resources to innovate more urgent aspects of the products;
2) Production/supply chain, if the reused designs allow reuse of production infrastructure and increased economies of scale [8];
3) Internal variety, by avoiding the introduction of parts to the assortment that add to the indirect (complexity-driven) costs of the product portfolio [4].
4) From a strategic viewpoint, design reuse can be used to help focus on the development of technological competences that make the company more competitive.

When these benefits are larger than the costs of reuse, we have *economies of substitution.* According to Garud, economies of substitution are present when greater technological progress is achieved by "substituting certain components of a technological system while reusing others" than developing the system from scratch [9].

The potential of improvement through better design reuse practices is probably obvious to most scholars and experienced product designers (e.g. [1]). It should not be too difficult to discover missed design reuse opportunities if one performs a post-mortem analysis of series of past product development projects. In this paper, we will explore possible approaches to counter such missed design reuse opportunities.

Design sharing

Although this paper focuses on reuse of design solutions over subsequent products, let us first consider the issue of *sharing* solutions across simultaneously existing products, especially product families where the products complement each other in the market. The question of *what* to share across concurrent products is what we could call the "design sharing problem", which could be formulated as: ***finding the optimum combination of shared and product-specific design solutions that minimises the lifecycle costs of a product family with given functionality requirements***. Several authors have contributed to solve this "sharing problem", from different viewpoints, such as: choosing the variety to offer to the market [10], choosing size ranges for shared components, [8][17], choosing product structure to allow for optimal balance between commonality and variety [20]. The main challenge in the design sharing problem is not conceptual, but comes among other factors from the practical difficulties of quantifying the true lifecycle costs and customer perceptions of the alternatives.

As suggested, the "design sharing problem" is concerned with a set of simultaneous products. This has two implications that are important to highlight here. The first is that the company context, notably technological and market knowledge, can be assumed constant during the development of the considered products. The second assumption is that there is negligible cost for transferring design solutions from one product to another. Designs can often be tested in several of the products under development that are to share them, and real-time feedback loops can facilitate adjustments.

The time factor

Now let us return to the issue of design reuse (i.e. over time). The two assumptions mentioned above normally do not apply, because in the general case:

1) Environments and capabilities drift from the time of development of one product to the next. The technological knowledge evolves because the company learns from research, experiences from previous products, the market and competitors. Furthermore, customer needs and preferences change.
2) The cost of transferring a solution from one project/product to another becomes significantly higher because of the time lag. There is no real-time feedback loop between the designers and the re-users of a solution. This transfer effort can sometimes even be larger than the effort to design the solution from scratch.

The time factor affects different functional areas of the products differently. While certain features may be stable (stable customer requirements and stable technology) others may be volatile. Some solutions may become obsolete from one product generation to the next. Other solutions may be sufficiently stable to enable reuse over several product generations. By *stability* here we mean the (potential) rate of evolution of the feature relative to the frequency of new product launches, which depends on the prevailing industry “clockspeed” [7]. As is discussed below, the ***predictability*** of requirements and opportunities in the foreseeable future determines how companies can capitalise on the stable while remaining flexible with regard to the unstable.

This paper

This paper intends to contribute to a perceived knowledge gap in the area of managing design reuse in contexts ridden with uncertainties. Specifically, the paper intends to categorise the main possible mindsets behind the decisions of what designs to reuse and what to be made reusable. While we here focus on the design of products, the reader should keep in mind that ideally the design of products should proceed in parallel with the design of other company assets such as the supply chain and the organisation. Design reuse is often an enabler for reuse of company assets, and consequently unfortunate design choices can obstruct the reuse of company assets.

Our research question is: *How can we formulate the main alternative approaches to design reuse that take the time factor into consideration?* The results are derived from a literature study and the development of theoretical constructs.

Three enablers of design reuse

We start by exploring the phenomenon of design reuse by grouping the main issues around three “requisites” for reuse, in order to study their nature, related costs and improvement potentials. (Table 1).

Table 1: Requisites for design reuse and possible improvement areas

Requisite	Issues	Action to improve
Availability of reusable design solutions	Technical aspects of design solutions (function, structure, match with supply chain, etc)	Invest in selective development of reuse-friendly solutions
Transfer of solutions	Possibility to capture, store and locate design information	Document for reuse, store in managed design database
Willingness to reuse	Understanding the benefits of reuse (direct/indirect costs and strategic impact)	Map reuse potential; manage reuse incentives and decision making

The availability of reusable design solutions

Most design solutions, of different levels of abstraction and detail of can be reused in one way or another. Even experience from failed solutions can be reused. Reused design solutions can be for example, components, interfaces and manufacturing choices. What we here vaguely call a design solution is the answer to a specific design problem and may have one or many designable dimensions or parameters (geometrical dimensions, material, finish, etc). Design solutions can be categorised in many ways. Often it can be useful to make a distinction between solutions representing “structure” (e.g. interfaces, functionality mapping) and solutions representing “content” (e.g. components). Design solutions may also correspond to more holistic properties of the products (i.e. indirectly decided by the lower level design solutions), such as overall weight.

Design solutions may be reused to different degrees. For example, when reusing components, all design parameters are replicated. When adapting a previous design solution, many but not all design parameters are replicated. In some cases, the reuse choice may concern a single design parameter. It is worth noting that two different components can have *commonality* from the viewpoint of a certain company asset, if it allows for reuse of that asset. For example, two components that use the same material may allow the reuse of a material supplier, regardless if the designs are based on different working principles. It is therefore important to identify design parameters that have significant impact on the lifecycles of the products.

Design solutions are often dependent on other design solutions. If highly interdependent, design solutions need to be reused in group. A reusable physical element, or “standard design” [14], should have unambiguous, well-defined interfaces and functionality. Modularisation methods aim at designing modules with such properties, and therefore make them more suitable for reuse, or “carryover” [6][2]. The relation between the product structure and the reused design solutions is here interesting to mention. While some designs have very simple interfaces and pose few constraints on the product structure, like nuts and bolts, other design solutions have complex interfaces and behaviour that poses considerable constraints on the product structure. Therefore, some product structures and module interfaces are more reuse-friendly than others. An approach to product structure that facilitates module reuse is presented by Smith and Duffy [19].

Often, an available previous solution will show to be slightly suboptimal for a new design problem. For example, a component may have been over-dimensioned to be able to function with different load requirements, thus weighting more than a product-specific solution would. This *overdesign* may in many cases result in a *performance slippage* or increased production costs [8][9][11]. This of course most often is an acceptable price to pay to get the benefits of reusing the solution.

The group of all past solutions we call the *assortment* of design solutions. This assortment has been built up throughout the product history of the company and contains solutions that have been deliberately designed for reuse (generic) and intended one-off solutions (product specific). The assortment of solutions normally increases as new products are added to the product history, because old solutions are often kept in one form or another in the company as new solutions are introduced. However, often only few of these solutions are technically adequate for reuse without modifications. To improve the possibilities to reuse, the assortment can be enhanced by designing for reuse. The challenge is that there cannot be any real-time request (pull) for such reusable solutions because of the time lag between design and reuse, so the initiatives must come from “visionary” forces within the company. Developing solutions for reuse can be considerably more expensive than developing for one product, because of the initial design costs and testing costs [9]. This investment should be amortised by the benefits of reuse perhaps over several product generations.

The means to transfer design solutions

For a design solution to be reused, the design information has to be transferred from the earlier project to a latter one. The information that the reusers usually need includes the design description (CAD-drawings, specifications), design rationale, test/simulation data, reuse advices, references to further sources of information, etc.

The costs related to the transfer of reuse information cost usually include [9]:

1) the effort to capture and update reuse information from the original designers. Documentation for reuse is often considered a “co-product” by development projects, which easily gets down prioritised when resources are scarce [5];

2) the effort of the potential reusers to search for and analyse available reusable solutions
3) the integration of the reused solution into the new product.

This transfer cost is usually negligible in comparison to potential long-term benefits of design reuse. But in some cases, the transfer cost has a short-term penalty on projects that discourages reuse, especially when it is more ***predictable*** to design a solution from scratch than to spend effort on searching for possible suitable past solutions.

In order to prevent the reuse information from being insufficient and scattered in different places of the company, it should be captured from the original designers in formal design language complemented by working language [1][19], and stored in a centralised searchable repository. Software-tools are almost indispensable for achieving this. Case-Based-Reasoning (CBR) is a theory about how humans solve problems that has been successfully used as basis for tools specifically developed for knowledge reuse. CBR-tools appear to be very useful to assist in the transfer of design solutions [3]. CBR is based on a process that includes the identification of potentially reusable solutions, a procedure for documenting relevant design and search information, and a structuring of the information for later retrieval. If successfully implemented and managed, such tools can make it so easy to search and retrieve past solutions, that the design reuse practices at the particular company can be radically improved.

Willingness to reuse

The willingness to reuse comes from the perceived benefits of reuse. As mentioned in the introduction, the possible benefits from reuse are of various types. Unfortunately, often it is difficult of quantify the true costs/benefits of different design alternatives. This is especially true when the cost structure of the design solution [17] has a large indirect cost share. Furthermore, the short-term and long-term objectives may conflict. This can of course work both encouraging or discouraging reuse. For example, it may be deemed disadvantageous in the short-term to reuse a solution (because it is faster to design it from scratch) but advantageous in the long-term because of smaller internal variety. Or, it may be advantageous in the short term to reuse a solution because it saves designing time, but disadvantageous in the long term because it hinders a lifecycle cost-saving improvement. It may be the case that there are no resources in the short-term to spend on changing an existing suboptimal solution.

Studies have shown that the initiative to reuse often is prevented by formal or informal incentives to design from scratch or cognitive obstacles such as engineers being sceptical about other designer’s solutions [5]. Furthermore, there is often a desire from the part of engineers to do product-specific optimisations that may be at the expense of reuse. Busby argues that the problems of (absent) reuse are more social than technical in nature. Another aspect is the question of *who* should take different reuse decisions. Some reuse decisions often have a considerable strategic impact. Ideally, classes of reuse decisions should be identified according to the appropriate decision forum. Reuse decisions with local impact should be made by designers guided by overall reuse rules. Decisions with strategic impact should be promoted to “product boards” or alike.

Factors determining the reuse approach

In this chapter, we study two related factors that determine the possible reuse approach.

The ability to forecast future reuse opportunities

To plan investments to increase the reuse benefits, companies need to forecast the requirements that will be put on their future products, and specifically try to predict future reuse opportunities. Predictions usually are reflected in product and feature road maps. A road map combines forecasts of factors that the company has no control over with plans for own actions, and is thus the tool that translates strategic considerations to the reuse approach. Reuse planners should assess the probability that different design problems (e.g. product features) will reappear in the future, and assess if the corresponding solutions are likely to remain "good enough" or become obsolete (expected rate of evolution). The accuracy of such forecasts greatly varies from company to company depending on factors such as technology maturity and market volatility.

Based on the predictability of reuse opportunities, technologies can be classified into:

1. product areas where "total innovation" is demanded, intentionally ruling out significant design reuse between products (except for "general" knowledge). Here there is little incentive to invest in efforts such as designing for reuse.
2. product areas where future product needs can be predicted and committed to. Here the "goal" is known, so the challenge is to find the optimal path, for example through the development of size ranges [17].
3. product areas that can be predicted to evolve (i.e. there is reuse potential), but the evolution direction/details are yet unknown. Here, in a sense, the goal is uncertain, but there are indications of what is convenient to reuse.

This predictability naturally affects how confidently a reuse planner can make decisions.

The timing of the reuse decision

Another important factor that shapes the design reuse approach is the timing when the decision to reuse a certain solution is made:

- in advance of the product development project (i.e. the particular reuse is *required* from the development project)
- during the project definition/conceptual phase, in advance of detail designing, i.e. the decided reuse is seen as having a value of its own other than meeting the actual product's functional requirements
- during the embodiment phase, as an ordinary means to aid in the product designing.

A company may benefit from deciding *in advance* to reuse ("freezing") if there is high confidence in the prediction of future needs. This confidence can come from the fact that the company operates in static/predictable environments, or that the company has the flexibility to shape its future through "normative forecasts". Arguably, whenever there is reasonable confidence that a future reuse opportunity will arise, companies should capitalise on with a formal decision to reuse. This is because:

- such an early decision can enable a *commitment* to get the most out of the reuse
- engineering teams will be able to assume the reuse will take place and optimise both the design to be reused and other surrounding designs accordingly
- at the later moment when the design solution is to be reused, no effort (generation of concepts, evaluation, coordination) needs to be spent on deciding which solution should be used to solve the particular design problem

See also Baldwin and Clark [2] who put forward strong arguments explaining the requisites and potential benefits of design decisions taken in advance, which they call "design rules".

However, in many cases the future design needs cannot be predicted with confidence enough to justify the risks of making an unfortunate decision, so it is more convenient to *postpone* the reuse decision. This critical level of risk should be identified to differentiate potential reuse decisions. This postponement decision should ideally be made explicitly, in order to assure that the necessary options are left open for the future. Figure 1 summarises the presented reuse approach alternatives.

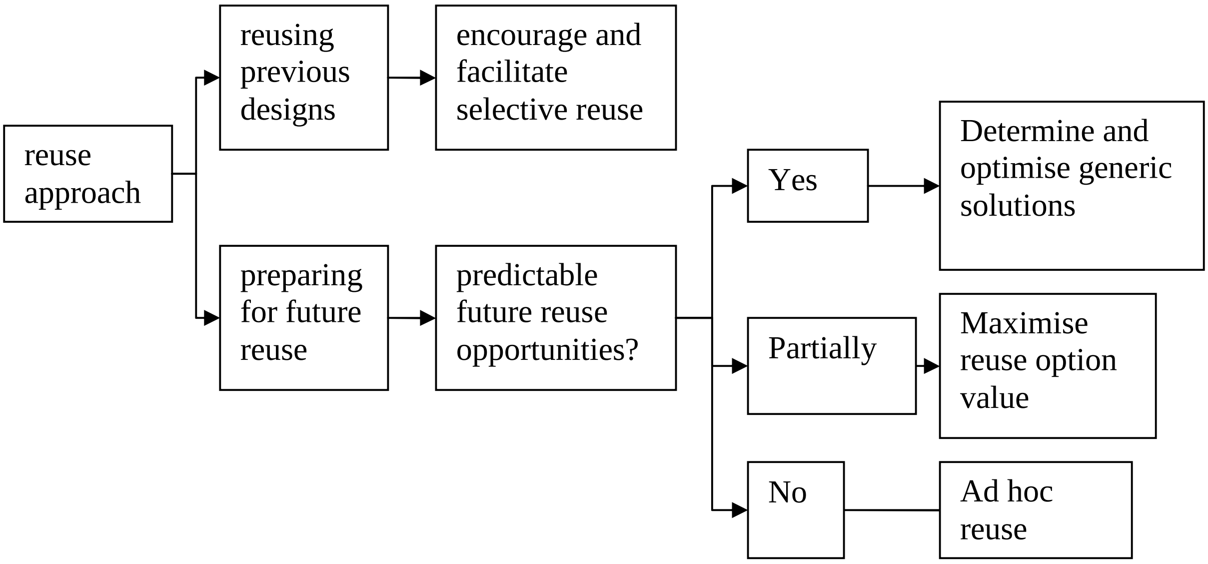

Figure 6. Reuse approaches depending on predictability of reuse

Reuse approaches

For different product areas, different reuse approaches are suitable. This section has categorised these into three: ad hoc reuse, planned reuse and option-based reuse.

Ad hoc reuse

When design reuse in products is decided on a case-by-case basis, and without considering future reuse, we can talk of ad hoc reuse. In ad hoc reuse, reuse of previous solutions is on-demand, i.e. triggered only by immediate needs (design problems). This could be seen as the “default” reuse practice at companies before proactive efforts are invested in exploiting more benefits from design reuse. Note that ad hoc reuse is not the same as absent reuse, and that companies can apply ad hoc reuse very consciously and efficiently, making use of all adequate opportunities to reuse. An effective practice of ad hoc reuse implies a *willingness* to reuse and proficient *transfer* of solutions (searching and evaluation of previous solutions). Companies that develop products that are so different that the opportunities for design reuse are minimal, probably do not have an interest in investing for improved reuse, and it may appear good enough for them to reuse in an ad hoc manner. Unfortunately, many companies seem to practice ad hoc reuse even though they probably would benefit from becoming more proactive in their reuse approach through investments in their assortment of solutions.

Planned reuse approaches

In planned reuse approaches, preferred design solutions are designed and designated for “obligatory” future reuse. Product platforms approaches are partially based on such planned reuse. In product platform approaches (as interpreted by some authors, for example [13][15]) a product family architecture specifies a set of generic design solutions (often subsystems) that are reused in a series of product variants. A central point of this kind of product platforms is that the generic solutions are deliberately *decided in advance* upon the designing of the product family architecture. Afterwards, because the platform design rules already have been decided, less effort (designing and coordination) must be spent each time a new variant is to be developed. Product platform strategies are especially suitable for companies where the set of solutions to be reused is relatively mature, so that it can remain competitive during the period when its value is to be exploited. Note that a platform strategy carefully chooses which design areas ("differentiating attributes") should be delegated to variant-specific design, which means in these product areas the reuse approach is of the ad-hoc or option-based kinds. Because the shared architecture of the products, including planned ones, is designed in one effort, then the "design sharing problem" can be solved to achieve an optimum commonality.

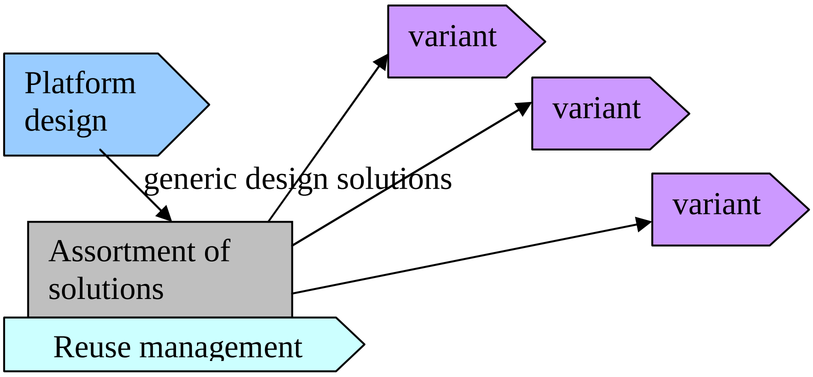

Figure 7. A platform approach; the decision to reuse is made a priori

Option-based reuse approach
In product areas where companies cannot predict future design reuse opportunities accurately, it may be desirable not to *predetermine* what should be reused in future products. In other words, it may be convenient to postpone the decision to reuse in order to keep as many design options open, even if it is expected that many of the solutions will actually turn out to be reusable. This "option-based" reuse approach should aim at providing flexibility for future projects to decide what they should reuse from the past, that is, maximising their possibility to capitalise on the deliverables of previous projects without restricting them. This should be done by improving the likeliness that selected new solutions will be reusable in the future – i.e. maximising their reuse potential – by preparing them for reuse.

Because it is not decided beforehand whether the solutions actually will be reused, the value of such preparation for reuse lies in the added *option* to reuse. "Real option valuation" is a decision tool that can aid in selecting which solutions to prepare for future reuse. The rule of thumb is to identify where investments can increase the "reuse option value" the most, by asking, for example: Is it possible to make a given design solution significantly more reusable through small technical adjustments? [2][10]

Managerial implications
Some requirements for "uncertainty-aware reuse management" are here proposed. Reuse management is here meant as the decision making that navigate companies in the "technological landscape" by means of deciding what to reuse and what to make reusable. Uncertainty-aware reuse management is needed to continuously control reuse between products that evolve rapidly, i.e. where there is great potential for reuse between product generations but the exact reuse needs are not predictable. This adaptive approach falls in line with the industry and research trend [12], and has deep similarities with Dynamic Modularisation [18], in that reuse is managed proactively and reusable designs are developed and introduced "continuously" to adapt to changing capabilities and environments.

Concretely, it is proposed that reuse management should have the following duties over subsequent product development projects (figure 3):
1) Monitor the reuse potential of old and new design solutions.

2) Select which previous solutions to reuse in products under development.
3) Select which new solutions to prepare for future reuse.

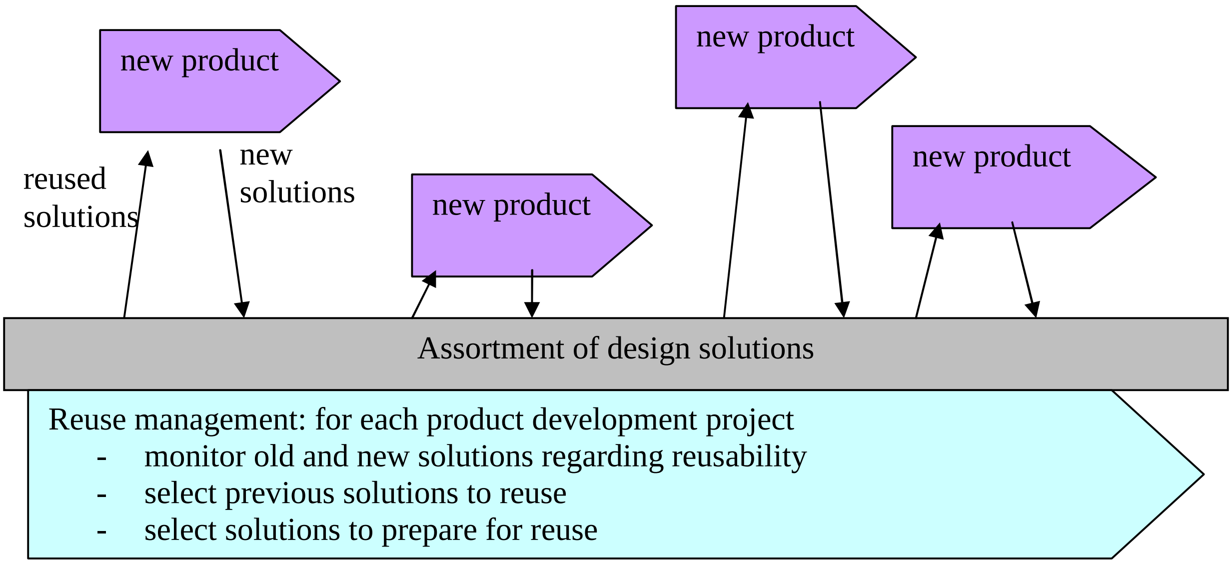

Figure 8. Continuous reuse management

The choice of reuse approach should ideally be explicit and clearly linked with product areas or technologies. Probably, most companies have product programs where all three reuse approaches are suitable in different product areas. For example:

- Stable "base" technologies could be predetermined as obligatory to reuse (planned reuse). This could apply to subsystems, and/or the product structure.
- Technologies that are important from a cost or customer perception point of view but rapidly evolving could be made as reusable as possible without predetermining their future reuse (option-based reuse).
- "Experimental" technologies could be left free to apply reuse in an ad-hoc manner.

For example, modularisation approaches could be interpreted as a combination of planned reuse (the product structure and the use of obligatory modules) and option-based or ad-hoc reuse (the implementation of the modules).

Conclusions

This paper has explored the elements of generational reuse approaches. The reuse approaches have been categorised according to the commitment and timing of the decision to reuse into ad-hoc reuse, planned reuse, and option-based reuse. Option-based reuse is an approach that makes use of real option-valuation to prioritise investments in reuse-friendliness. The need for an uncertainty-aware management of reuse has been suggested and its basic duties outlined. Such an approach should have as goal to maximise the positive effects of reuse despite the uncertainties discouraging investments in reuse. One limitation of the proposed modelling of reuse approaches is that in reality often decisions are taken gradually. Despite this, it is hoped that this paper contributes to future research in how to deal with uncertainty when deciding reuse policies at companies.

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