INTERNATIONAL DESIGN CONFERENCE - DESIGN 2014
Dubrovnik - Croatia, May 19 - 22, 2014.

VALUATION OF PRODUCT ADAPTABILITY IN ARCHITECTURE DESIGN

P. Schrieverhoff, R. de Neufville and U. Lindemann

Keywords: valuation, adaptability, flexibility, system architecture

1. Introduction

The evolution of stakeholder needs and the resulting desire to adapt system properties to those needs most adequately is a topic increasingly addressed in literature. [Woodruff 1997], [Bartolomei et al. 2006], [Browning and Honour 2008], [Engel and Browning 2008]. Reasons are manifold. On the one hand the overall lifecycle value of systems can be increased, their active lifetime prolonged and the users be more satisfied. On the other hand adaptability in system properties offers very immediate advantages during the design phase and system completion. It can be applied as a measure of risk management to mitigate the effect of uncertainties and changing requirements as it offers the option to save time and money in future [Cardin et al. 2007].

While the benefit of adaptions is rarely expressed quantitatively [Browning 2003], the cost associated to the process of enabling adaptability at a later stage is very apparent during the conceptual design phase, in which system designers decide between different technical alternatives - defined as *Architectures* in the course of this paper. Additional resources have to be allocated to enable a reconfiguration of the system by addition, exchange or subtraction of system-components and have to be justified by an expected benefit. The more concrete the benefit can be expressed in monetary numbers, the more substantiated the decision.

The valuation of flexibility has been addressed in recent years by *Real Options Analysis* (ROA). Analogies between the option to change a system parameter and financial options are established within that area and financial methods like the *Black-Scholes-Formula*, *Binomial Lattices* and *Monte-Carlo-Simulation* applied on physical projects [de Neufville 2003], [Wang 2005]. Later approaches have proven to be potent in the context of a *Expected Net Present Value* (ENPV) *Calculation*, but are so far typically applied to scaling a singular system parameter in large projects, that can be assigned a clear payback-function [de Neufville et al. 2009].

This paper builds on the fundamentals developed within the field of ROA to determine the value of adaptability under uncertainty, coined *Option Value* (OV) in accordance with established terminology in the field. The paper contributes to the identification and assessment of the decisive *Key Parameters* (KPs) of systems, especially the monetization of those performance criteria and the consideration of technological progress. The concept of value in engineering systems and the contribution of the alteration of singular system parameters towards it is elaborated on and illustrated in the context of an industrial case study. To pay tribute to the crucial influence of uncertainty both from the technological and from the market point of view, the approach allows all input parameters to be taken up with assigned distributions of probability and not as sharp values. Using Monte-Carlo Simulation a large number of possible future scenarios are mapped transparently and allow the value of adaptability to be assessed over time and under uncertainty. To enable an in-depth interpretation by system designers, a selection of metrics to relate the value of adaptability to the system under development is presented and discussed.

2. Background and motivation

Adaptability

Adaptability is one of the so called *-ilities* – a system property that describes desired behavior but is neither well defined nor easily evaluable in isolation [de Weck et al. 2011]. Ilities are considered to have substantial influence on how well a system performs over its lifecycle, but are generally neither explicitly addressed by requirements nor assigned a concrete budget in the product development process.

A wide body of literature addresses the advantages of adaptable systems. Fricke and Schulz [2005] stress that the three main drivers for system development – the marketplace, the technological evolution and the variety of environments – are becoming more and more dynamic. Therefore system require responsiveness. Browning and Honour [2008] further state that stakeholder needs evolve over time and cannot possibly be perfectly met with a static design. De Neufville [2003] emphasizes that uncertainty is inevitable and poses both risk and opportunity. McManus and Hastings [2006] consider adaptability a means of both mitigating the risks as well as exploiting the opportunity. In conclusion it can be said that increasingly dynamic environments and contextual factors, longer system lifecycles as well as rapid technological evolution impose the importance of adaptability as a system property.

Adaptability as a term is often confused with or considered synonymous to flexibility. [Hashemian 2005] defines adaptability a means for creating designs and products that can be easily modified for different requirements by an external agent, which is in line with the understanding of Gu et al. [2009], Engel and Browning [2008], Browning and Honour [2008] and Fletcher et al. [2009]. For Fricke and Schulz [2005] and Ross et al. [2008] this definition meets with understanding of flexibility, though, and they consider adaptability to be an intrinsic property of the system to adapt itself to different requirements or boundary conditions autonomously. The reason for the different definitions can to some degree be found in the fact that adaptability and flexibility are terms of the habitual language and not originally coined by science. In the course of this paper the dictionary definition [Merriam-Webster 2004] is followed, which defines the terms as follows: *to adapt* stands for "to make fit (as for a new use) often by modification" and adaptable stands for "capable of becoming adapted". In contrast, the word *flexible* is explained as "capable of being flexed", "yielding to influence" or "characterized by a ready capability to adapt to new, different, or changing requirements". According to this definitions *adaptable* can be considered as "capable of extrinsic modification" whereas *flexible* can be considered as "capable of intrinsic modification"[Kissel and Schrieverhoff 2012]. Many researchers do not differentiate the terms [Suh et al. 2007], [de Neufville and Scholtes 2011] and for this piece of work also the clarification of the terms to the reader is of higher importance than the terminology.

[Ross et al. 2008] characterize adaption (or change in general) by three elements *(1) the agent, (2) the mechanism* and *(3) the effect*. The agent of adaption is the instigator, or force, for the change. The effect is the difference in states before and after a change has taken place, and often it is the effect that is first noticed to indicate a change has occurred. The mechanism is the path the system must take in order to transition from its prior to its post state. A change path details the necessary components to bring about the change, including conditions, resources, and constraints for the change.

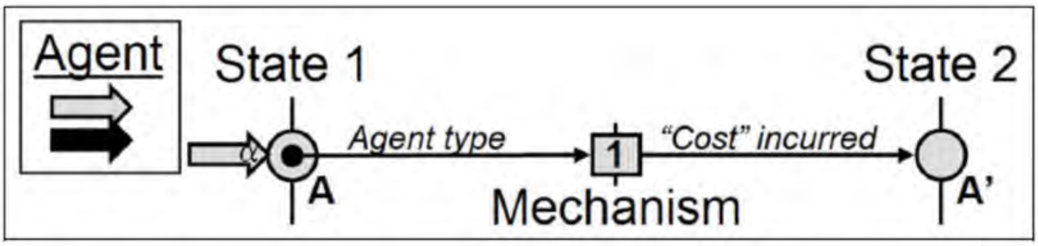


Figure 1. The three aspects of a change. Change defined as state transition [Ross et al. 2008]

Further Ross et al. [2008] classifiy three categories of effects: *robustness, scalability*, and *modifiability*, which refer to a parameter-based description of a system capturing physical, functional, and other performance aspects. Robustness is the ability to remain constant in output in spite of system internal and external changes. Scalability is the ability to change the level of a parameter. Modifiability is the ability to change the membership of the parameter set. Hashemian [2005] introduces three categories of adaptability: *(1) product vs. design adaptabily, (2) specific vs. general adaptability and (3) sequential vs. parallel adaptability*, whereas the last differentiation is of no importance to this paper.

Specific adaptability means that a system is developed to comply with expected future needs. Unlike the conventional design process in which a product is designed for a nominal set of requirements, it is developed to be adapted to different or additional functions beyond their normal operational mode on the basis of forecast information. *General adaptability* is more a concept than a design characteristics which make a product generally more adaptable, in particular to unforeseen changes. This attribute is supposed to increase the lifetime of the system by gaining the independence of any external changes in its service environment. To design products or system for general adaptability that mostly relate to architecture and interfaces such as modularity. *Design adaptability* refers to the reuse of designs and results in the creation of a variety of designs based on a common adaptable blueprint (variants), and in the upgrading of new models through the modification of old designs (versions), which is mostly performed by the producer of a system and therefore also called producer adaptability. In contrast *Product Adaptability* describes the ability of a single physical product to be used for different service requirements. The adaptation task is usually performed by (or at) the user, so it can be also called user adaptability. User adaptations include the upgrading and customization of products as well as the attainment of several functions from a single versatile product. The work at hand addresses *specific product adaptability*, meaning that a physical system in operation is assessed towards specific parameters determined by forecasting techniques.

Design for Adaptability (DfA)

Hashemian [2005] names *Design for Adaptability* (DfA) as a new design paradigm among the family of *Design for X*, that has the goal of developing products with greater adaptability. According to him DfA (or also *Adaptable Design*) is particularly characterized by the fact that an adaptable system is designed to change its operational mode in some circumstances, whereas conventional mechanical systems are designed to a fixed set of requirements to fit one normal operational mode. This is in line with [Gu et al. 2009] who states that DfA aims to create designs and products that can be easily adapted for different requirements.

It becomes obvious that DfA implies a lifecycle perspective, to which further authors attribute importance. Browning and Honour [2008] stress that most large, complex, and expensive systems are anticipated to have a fairly long life cycle, and even simpler systems' life cycles are extending from the perspective of the product platforms that give rise to multiple product generations. Therefore, designers must consider not only how to meet specifications that will satisfy stakeholders today but also the trajectories of markets and technologies that will determine what it takes to satisfy stakeholders in the future. According to the authors carefully forecasting and systematically updating and improving predictions as more information becomes available, is an essential aspect of designing for maximum *Lifecycle Value* (LCV).

Ross et al. [2008] discuss shifts of systems ownership from the customer to the supplier as another important aspect of increasing consideration of life cycle cost and state that including future change costs will need to be considered more by the supplier than in the past.

The objective of DfA lies in optimizing a systems performance and thereby value over its entire lifecycle under considerations of uncertain and changing boundary conditions and contextual factors as well as cost considerations [de Neufville 2003], [Cardin et al. 2007], [Engel and Browning 2008], [Fitzgerald 2010]. McManus and Hastings [2006] describe that the current environment of rapidly changing technologies and markets imposes the need for more mature methods for the design of flexible or evolutionary systems.

While Fricke and Schulz [2005] point out that all three determining drivers of system development – namely the marketplace, technological evolution as well as variety of environments – become more and more dynamic and thereby increase the value of adaptability, they also state that more adaptable systems are usually associated wigh higher upfront cost in system development and underline the importance of determining the right degree of adaptability, as depicted in Figure 2.

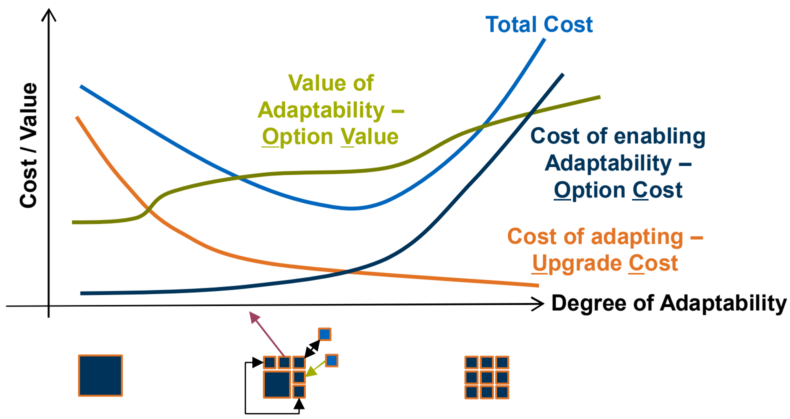


Figure 2. Cost vs. Value of Adaptability comp [Schulz et al. 2000]

Engel and Browning [2008] and Browning and Honour [2008] also call for a method to help designers determine the optimal amount of adaptability a system that exhibits highly uncertain future requirements should possess, since point forecasts of the distant future are almost always wrong.

3. Approach and application

To quantify monetary benefits an *Expected Net Present Value* (ENPV) calculation under uncertainty is executed. In finance, the *Net Present Value* (NPV) of a time series of cash flows, both incoming and outgoing, is defined as the sum of the *Present Values*. NPV is a central tool in *Discounted Cashflow* (DCF) analysis and is a standard method for using the time value of money to appraise long-term projects [de Neufville and Scholtes 2011]. This means that in each period the revenues created by adaptability within a system as well as the spending associated with it are added up and discounted back to the present point of time. In order to be able to do that the mechanism of value generation behind the *Key Paramers* (KPs) affected by an adaption are elaborated on and utilized for a monetization of benefits.

An ENPV calculation takes uncertainty into account by running several NPV calculations under volatile boundary conditions and thereafter averaging the results and outlining their distribution. Depending on the technological progress, it is determined by Monte-Carlo Simulation which sales and cost advantages are achievable by which architecture. System KPs with no direct connection to cashflows are converted into monetary terms, whereas technological and market uncertainties are considered. Furthermore technological boundary conditions like possible times of the upgrade are considered in the calculation.

The effect of adaptability in terms of monetary benefit in comparison to the spendings implied for it is evaluated over time. The results are attained in a four step process and laid out as distributions enabling an in depth interpretation and the consideratrion of risk aspects (comp. Figure 3).

Figure 3. Graphical overview of methodology steps

First KPs are identified and assessed, in order to objectify which system properties provide value if designed adaptably and to describe the mechanism of that value generation. This step takes place on an abstract level and is in principle independent of the technical implementation of the system.
In the second step different technical design alternatives, coined as Architectures, are assessed towards their KP profile. Here the constellation and extent of alteration of its KPs by adaptability as well as the boundary conditions for its utilization are of interest.
The value of an adaption (Option Value) is absolutely dependent on the development of technology and market conditions. Those two factors are assessed in the third step and the probabilistic input data for the Monte-Carlo Simulation in the next step is derived.
In Step 4 the ENPV calculation is conducted and the interpretation of the results takes place. The distribution of NPV as well as *Return on Investment* (ROI) are discussed and elaborated on. The procedure is developed with the claim to be applicable for most technical systems due to its generic set up. Only for illustrative reasons it is subsequently presented in detail along a concrete industrial example.

Industrial Example

The industrial case-study in this research is chosen to be the *Cap Applicator* (CA) within a Beverage Packaging Line as depicted on Figure 4 because it covers many aspects of value generation in technical systems. The main function of the equipment is to apply the caps onto beverage packages, e.g. milk or juice cartons. The project partner manufactures the packaging lines, whose customers actually produce the beverages and sell to retailers. The goal of the research to assess which architecture of the cap applicator is beneficial in terms of allowing later adaptability and generating extra value by enabling changes of KPs of the packaging line to altered boundary conditions. It is assumed that by adding value for the customer, the manufacturer of the packaging lines gains a competitive advantage against rival companies and technologies.

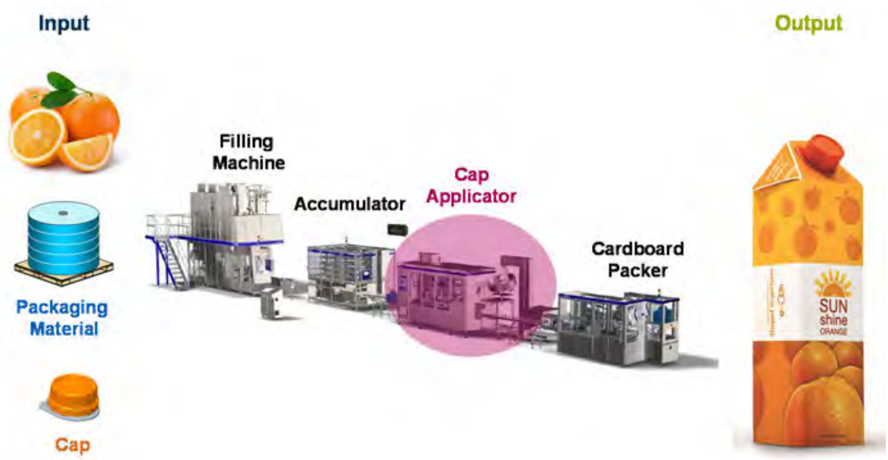


Figure 4. Cap Applicator in a beverage packaging line

Step 1: Identification and Assessment of Key parameters of Value

The first step of the Valuation concerns the identification of attributes that provide most value if being designed adaptably. Those attributes, defined as KPs in the previous sections, capture physical, functional, and other performance aspects that are of subjective value to one or several stakeholders [Ross et al. 2008], [Browning and Honour 2008]. They can enable a system to take profit from opportunities or protect it against risk and threats.
Literature sets out several methods that can be applied. Ranging from intuitive methods like *customer and stakeholder interviews*, *group discussion*, *brainstorming* and *surveys*, semi-analytical methods like the *Delphi-Method*, *Scenario Technique* or *TRIZ Trends of Technical System Evolution* as well as fully analytical methods like the *analysis of requirements evolution and changes* are named. The *Hierarchy of Customer Value* can also aid in the process of understanding which product attributes are

mostly involved in providing positive consequences and goal achievement for the customer [Woodruff 1997]. Browning and Honour [2008] state that stakeholders often will rather list KPs of operational nature, like *Maintenance Cost*, than technical parameters like *Mean Time between Failures*, which underlines that the KPs named must be reviewed and aligned. The decision on which method to apply typically depends on the boundary conditions and situational factors [Lindemann 2009]. Among those are available resources (personnel, budget, expertise, data), the available time and knowledge as to the use and application of the methods. In the research at hand multi-stage expert interviews were conducted and the main KPs *Number of Closure Types*, *Number of Package Types*, *Energy Efficiency* and *Eco-Class* identified.

A deeper understanding of different characteristics of KPs in the engineering context is paramount for a valid value assessment. Value emanates from the right, but not the obligation to adapt the system in terms of KPs to better fulfill stakeholder needs. Depending on market opportunities such as niche markets opening up, or technological progress, an adaptable architecture allows one or several adaptions of the system in order to improve KPs or lower operational cost. For the assessment of value three categories with general applicability are distinguished: *Revenue increases*, *Cost cuts* that can be converted into a monetary value for the customer and *Add-on Features* for which the customer exhibits a *Willingness to Pay* (WTP), as depicted in Figure 5.

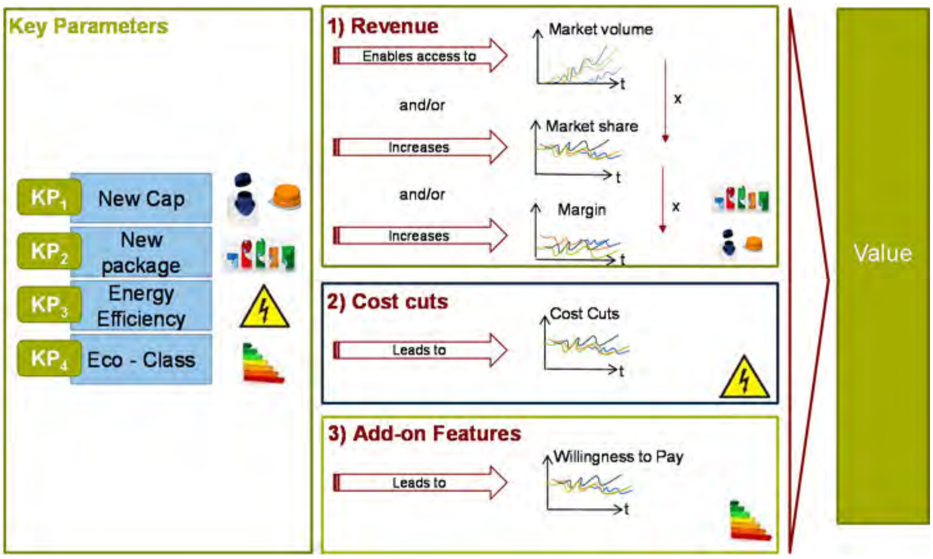


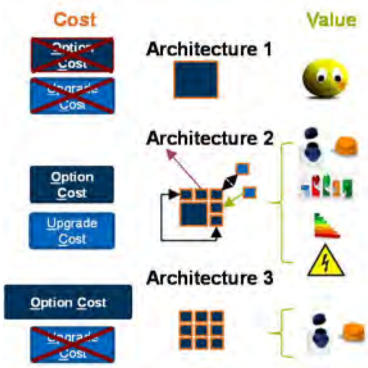
Figure 5. Mechanisms of value generation

Within the industrial example the KPs *Number of Closure Types* and *Number of Package Types* can be mapped onto either the *market share* or *margin*, in cases of extreme innovation even increase or creation of the *Market Potential*. As soon as a new closure or package type can be produced by the beverage line, the market is accessible and the achievable *Revenue* for the producer depends on the market volume, the market share and the margin. The *Energy Efficiency* is an example for a KP achieving a *Cost cut*, which leads to a very well calculable advantage in electricity spendings. Cost cuts are determined by the decrease in cost per e.g. one thousand cartons produced. An improvement in *Eco-Class* achievable by an upgrade represents an *Add-on Feature*. The value of such a KP depends on its extent, meaning on how much of it (units) can be provided by technology at the time of the adaption. Within the piece of work the customer is expected to exhibit a *WTP* of $2000 for every level of *Eco-Class* improvement. The mechanisms of value generation are assumed to be mutually exclusive and cumulative exhaustive and able to describe the conversion of technical KPs to monetary terms for technical systems in general.

Step 2: Architecture Assessment towards Adaptability

The Cap Applicator can be designed in different technical ways, which is represented by the term *Architecture*. Each of those Architectures provides a unique profile as to which KPs can be adapted to

which extent and at what cost. Adaptable architectures allow a substantial change of KPs and therefore enable the reaction to changed boundary conditions, whereas rigid or monolithic architectures allow very little change of KPs. Within the project three alternative architectures in terms of adaptability have been identified based on complexity analysis and the experience of the Closure Applicator team.
Architecture 1 represents the current*, rigid design*, Upgrades are not possible and/or convenient and a change in customer needs or further boundary conditions can only be reacted to by replacing the entire cap applicator with new equipment. It provides a base-line for assessing the value and cost of adaptability of the alternative Architectures. *Architecture 2* represents an *adaptable design.* An Upgrade is feasible and can be achieved by replacing certain components - guides and further parts with modified geometrical dimension will be inserted at need. Architecture 2 allows all named KPs to be adapted – namely the *Closure type*, *Package type*, *Energy Efficiency* and *Eco-Class*. *Architecture 3* represents a design prepared for a wide range of changes upfront. No new parts are needed for an upgrade but a change in specifications is reacted to by modifying settings and inserting/removing shims in the guides. It enables the customer to switch to different *closures* quickly, but comprises high upfront cost. Furthermore it is not possible for it to handle other package *types* and technological progress that occurs after installation of the system cannot be integrated afterwards, thus neither *Energy Efficiency* nor *Eco-Class* can be improved (comp. Figure 6).



	Option Cost	Upgrade Cost	Key Parameters	Boundary conditions
Architecture 1	-	-	-	-
Architecture 2	140,000	46,000	Closure Type Package Type Eco-Class Energy Efficiency	Upgrade once per year
Architecture 3	246,000	0	Closure Type	Upgrade anytime

Figure 6. Constellation of OC, UCand KPs for different architectures

Architectures exhibit different profiles as to the cost of adapting the system to a designated change. In accordance to option theory, two terms of cost are distinguished, *Option Cost (OC)* and *Upgrade Cost (UC)*. Option Costs cover all expenses that enable a future adaption within a system. Those expenses occur in any case, independent of whether the option is activated, i.e. the adaption is performed, or not. OC comprise all engineering effort needed to devlop and physically incorporate an option into the system (static) as well as effort needed to maintain the option (running) [Kissel and Schrieverhoff 2012].
UC comprise all engineering and physical effort needed to actually adapt a system (static) as well as additional running cost that are caused by the adaption (e.g. higher energy consumption). Even though costs can usually be estimated more accurately than value aspects, it is still important to document the uncertainty for further consideration in the simulation. Boundary conditions for adaptions like possible times of an upgrade have to be documented and taken into account in the calculation as well.

Step 3: Market and Technology Forecasting

The uncertainties that drive the value of adaptability can be generally categorized into market uncertainties and technological uncertainties (comp. Figure 7). Technological uncertainties exist in terms of readiness (timing) and enhanced performance of upgrades to be applied in the adaptable *Architecture 2*. Technology forecasting [Orloff 2006] is used to determine the development of KPs, whereas a Monte-Carlo-Simulation under consideration of uncertainty is applied. In case of internal development the duration of development as well as its uncertainty in timing and performance increase is considered. In case of external development the former development is reviewed and extrapolated.

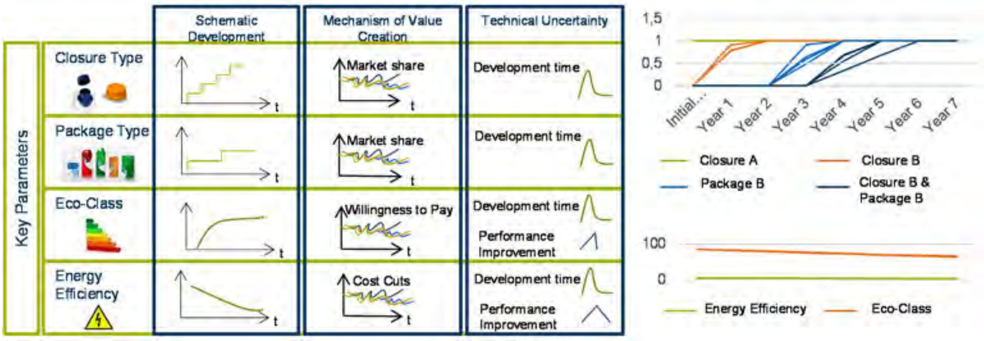


Figure 7. Overview technology forecasting under uncertainty

Figure 7 depicts the KP Development. *Closure and Package types* are discrete Key Parameters – if their status reaches "1" it means an upgrade to integrate them into the manufacturing line is available. They enable the access to certain markets when available. *Energy Efficiency* and *Eco-Class* are (quasi) continuous in their development, the lower they get the more valuable is an upgrade to the system.
Market uncertainties comprise changes in demand for certain closure and package types. Within this piece of work historical variance and contextual factors are distinguished as sources of uncertainty. While the historical variance represents the general volatility of a parameter, the contextual factors are mapped on top to account for concrete trends or developments considered probable in the future. Forecasting techniques are commonly classified in judgmental (also intuitive) and statistical methods (also quantitative – even though judgmental methods can be quantitative, too). Where judgmental methods rely mostly on expert estimation and opinion, statistical methods make use of extrapolation techniques based upon existing data. Hybrid forms combine both sources of data [de Neufville and Scholtes 2011]. In the context of engineering systems, available data is frequently scarce, in various forms and formats and often not easiliy accessible. This might be the reason why many authors [Hashemian 2005], [Browning and Honour 2008], [Engel and Browning 2008], [Gu et al. 2009] recommend the use of intuitive methods like scenario technique, Delphi-method, Customer and Stakeholder surveys, and Expert Interviews. De Neufville and Scholtes [2011] describe the use of statistical and hybrid methods for the use of demand forecasts. The choice of method therefore depends on the situational factors of the application context. Figure 8 is based upon a pragmatic approach feasible in most industrial use-cases, that takes up market forecasts and adds a factor of uncertainty in order to represent possible future variations. The uncertainty is in this case represented by a triangular distribution of percentual variance from the initial point estimate. The market share furthermore depends on technological progress, since a market for *Package type B* for instance can only be accessed by adaptable *Architecture 2* if the technology is ready to be implemented.

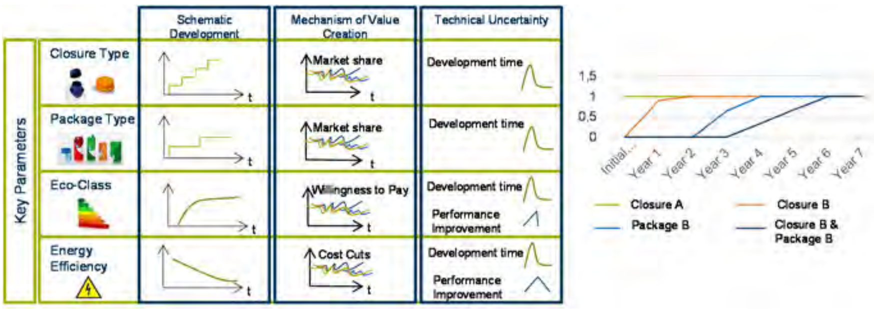


Figure 8. Market volume, market share and margin under volatility

Special attention has to be paid to contextual factors (society, legislation, etc.) overlaying historical development and changing the course of development (possibly trend breakers). Those can be identified and quantified in expert interviews and be mapped onto the extrapolation of the market data for instance. The contextual factors can be stationary or comprise uncertainty themselves and be dynamic. As Figure 9 depicts, the assessment of the contextual factors includes the analysis of their influence on KPs. It is differentiated if *Revenue aspects* (market volume, market share, and margin), *Cost aspects* or *Add-on* Factors are impacted on. Furthermore the factors could be interdependent and correlate.

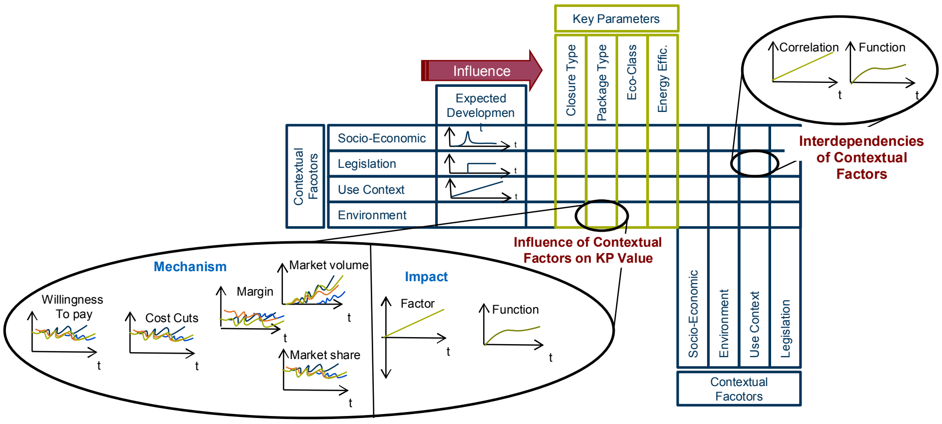


Figure 9. Overview interdependence of contextual factors and key parameters

For example, the contextual factor *Legislation*, which is expected to exhibit a law for stricter recycling requirements, might have a negative influence on the Market Potential of Closure A (recycling unfriendly) and a positive influence on the *Market Potential* of Closure B (recycling friendly) as well as *Margin* of Cap B, and further influence the Customer behaviour within the *Use Context*.

Step 4: Simulation and Interpretation of Results

To quantify the monetary benefit an *ENPV* calculation under uncertainty is executed. Depending on the simulation of the technological progress and market uncertainties, it determines which *Revenue* and *Cost* advantages are achievable by which Architecture. It is evaluated on a yearly basis which additional profit or cost cuts would occur for the owner of the system. Furthermore it is assessed if there are *Add-on* Features available towards which the system owner exhibits a *WTP*, e.g. an improvement in *Eco-Class*. Boundary conditions like possible times of the upgrade are taken into account in the calculation.

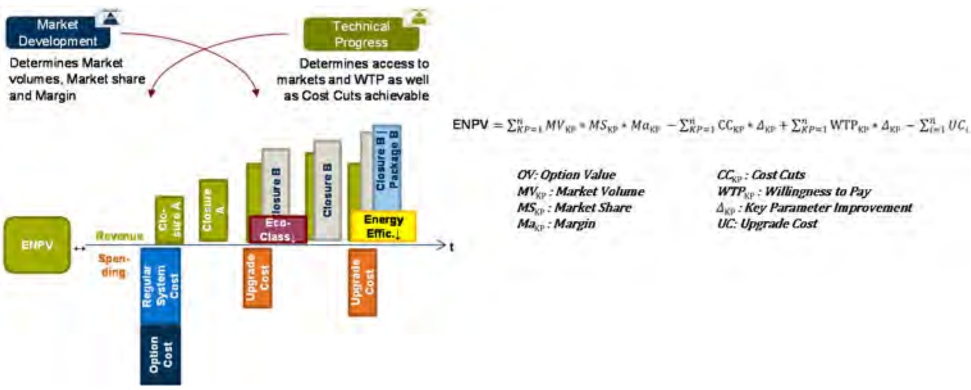


Figure 10. Simulation model

The model simulates how market demand develops on the one hand and which opportunities arise for additional sales. On the other hand it is simulated which technological means will be available in order to fulfill demand (and when) or cut cost. By exercising an upgrade additional incomes (sales) as well as costs (material, downtime) occur.

The probability distribution of *ENPV* is depicted on the following figure. While the expected value is of high importance, so is the overall shape, allowing for an in-depth interpretation of risk aspects.

The data on Market development was assumed and the actual numbers are to some degree hypothetical, therefore the results shown below should be read qualitatively rather than quantitatively. Architecture 2 outperforms the other architectures and is (quasi) stochastically dominant and shows an

ENPV of 126.000 in comparison to 91.000 of the rigid design of *Architecture 1* and 53.000 the flexible design of *Architecture 3*. *Architecture 2* profits from comparatively little upfront cost and dynamic reaction to opening markets. Within the simulation an upgrade was conducted whenever the average demand for a certain closure or package type was above 10.000 k units for two years in a row. The flexible design of *Architecture 3* comes at a high upfront cost and only enables access to markets requesting another closure, but not another package and therefore performs badly under the estimated market conditions.
To further assess the different Architectures the *Return on Investment* (ROI) has been taken into account. Using *Architecture 1's Rigid design* as a baseline the relation of additional income to additional expenses was compared for *Architecture 2* and *Architecture 3*. Where *Architecture 2* exhibits a ROI of 1,15 representing a profitable investment, *Architecture 3*'s ROI is 0,85 and therefore the upfront spending for OC are not amortized by value generation during the contemplated period.

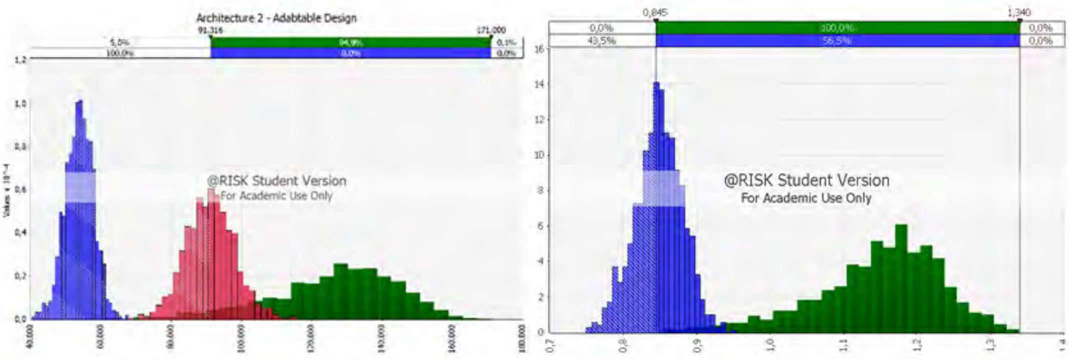


Figure 11. Expected Net Present Value (ENPV) & Return on Investment (ROI) Distribution

4. Conclusion and discussion

The approach presented in this paper allows the value of adaptability to be assessed over time and under uncertainty. A systematic procedure is presented that utilizes an *Expected Net Present Value* calculation to quantify the monetary of the alteration of system Key Parameter based on their impact on Revenue, Cost cuts and Add-on Features towards which a Willingness to pay exists. By *Monte-Carlo Simulation* the distribution of possible Net Present Values ans well as the Return on Investment is calculated and can be assessed over time and under consideration of risk aversion aspects. The approach is illustrated along an industrial example but exhibits general applicability for technical systems.
A large factor of uncertainty remains the current input data. Momentarily the forecasted data including a distribution for uncertainty is used for the market forecasts. This does not represent a random walk, though, but only oscillates around the fixed market forecasts and does not exhibit as much variability. Furthermore the influence of the contextual factors has been estimated based on experts opinion and not been calibrated on statistical data. A sensitivity analysis carried out [Wang and de Neufville 2006] lists not one contextual factor among the ten most influential input parameters on the NPV of *Architecture 2*, which means that currently the volatility of the market strongly overrules the influence of the contextual factors. This is part due to the fact that no “real” trend breakers have been identified, but also because due to the modelling applied.

References

Bartolomei, J. E. et al., "Screening for Real Options“ In” an Engineering System: A Step Towards Flexible System Development--PART I: The Use of Design Matrices to Create an End-to-End Representation of a Complex Socio-Technical System", In INCOSE Conference on System Engineering Research, Los Angeles, CA., 2006.

Browning, T. R., "On customer value and improvement in product development processes", Systems Engineering, 6(1), pp. 49–61. Available at: http://doi.wiley.com/10.1002/sys.10034 [Accessed November 13, 2012], 2003.

Browning, T. R., Honour, E. C., "Measuring the life-cycle value of enduring systems", Systems Engineering, 11(3), pp.187–202. Available at: http://dx.doi.org/10.1002/sys.20094, 2008.

Cardin, M.-A. et al., "Extracting value from uncertainty: A methodology for engineering systems design", In 17th Symposium of the International Council on Systems Engineering, San Diego, CA, United States. Citeseer, 2007.

De Neufville, R. et al., "Identifying real options to improve the design of engineering systems", H. B. Nembhard & M. Aktan, eds. Real Options in Engineering Design Operations and Management, 02138(July), 2009, pp. 1–37.

De Neufville, R., "Real options: dealing with uncertainty in systems planning and design", Integrated Assessment, 4(1), 2003, pp. 26–34.

De Neufville, R., Scholtes, S., "Flexibility in Engineering Design (Engineering Systems)", The MIT Press. Available at: http://www.amazon.com/Flexibility-Engineering-Design-Systems/dp/0262016230 [Accessed November 24, 2012], 2011.

De Weck, O. L., Roos, D., Magee, C. L., "Engineering systems: Meeting human needs in a complex technological world", The MIT Press, 2011.

Engel, A., Browning, T. R., "Designing systems for adaptability by means of architecture options", Systems Engineering, 11(2), Available at: http://dx.doi.org/10.1002/sys.20090, 2008, pp. 125–146.

Fitzgerald, M. E., "Managing uncertainty in systems with a valuation approach for strategic changeability", 2010.

Fletcher, D., Brennan, R. W., Gu, P., "A Method for Quantifying Adaptability in Engineering Design. Concurrent Engineering", 17(4), 2009, pp. 279–289.

Fricke, E., Schulz, A. P., "Design for changeability (DfC): Principles to enable changes in systems throughout their entire lifecycle", Systems Engineering, 8(4), 2005, pp. 342–359.

Gu, P., Xue, D., Nee, A., "Adaptable design: concepts, methods, and applications", ... of the Institution of Mechanical Engineers ..., 223(11), Available at: http://pib.sagepub.com/content/223/11/1367.short [Accessed November 10, 2013], 2009, pp. 1367–1387.

Hashemian, M., "Design for adaptability", Saskatchewan, Canada, 2005.

Hashemian, M., "Design for adaptability", Saskatchewan, Canada. Available at: http://citeseerx.ist.psu.edu/viewdoc/summary?doi=10.1.1.134.2831 [Accessed October 11, 2013], 2005.

Kissel, M., Schrieverhoff, P., "Design for Adaptability – Identifying Potential for Improvement on an Architecture Basis", 2012.

Lindemann, U., "Methodische Entwicklung technischer Produkte: Methoden flexibel und situationsgerecht anwenden", Springer DE, 2009.

McManus, H., Hastings, D., "A framework for understanding uncertainty and its mitigation and exploitation in complex systems", IEEE Engineering Management Review, Available at: http://mit.sustech.edu/NR/rdonlyres/Engineering-Systems-Division/ESD-85JFall-2005/695980D5-FDEE-4C4D-A505-14B8E9C95841/0/uncertainty.pdf [Accessed November 7, 2013], 2006, pp. 1–19.

Merriam-Webster, "The Merriam-Webster Dictionary", Merriam Webster Mass Market. Available at: http://www.amazon.com/The-Merriam-Webster-Dictionary/dp/087779930X [Accessed November 10, 2013], 2004.

Orloff, M. A., "Grundlagen der klassischen TRIZ: Ein praktisches Lehrbuch des erfinderischen Denkens für Ingenieure (VDI-Buch) (German Edition)", Springer. Available at: http://www.amazon.com/Grundlagen-klassischen-TRIZ-praktisches-erfinderischen/dp/3540340580 [Accessed February 28, 2013], 2006.

Ross, A. M., Rhodes, D. H., Hastings, D. E., "Defining changeability: Reconciling flexibility, adaptability, scalability, modifiability, and robustness for maintaining system lifecycle value", Systems Engineering, 11(3), 2008, pp. 246–262.

Schulz, A. P. et al., "Development and integration of winning technologies as key to competitive advantage", Systems Engineering, 3(4), 2000, pp. 180–211.

Suh, E. S., De Weck, O., Chang, D., "Flexible product platforms: framework and case study", Research in Engineering Design, 18(2), Available at: http://dx.doi.org/10.1007/s00163-007-0032-z, 2007, pp. 67–89.

Wang, T., "Real options“ in” projects and systems design: identification of options and solutions for path dependency", 2005.

Wang, T., de Neufville, R., "Identification of real options “in” projects", In 4th Conference on Systems Engineering Research, Los Angeles, CA, 2006.

Woodruff, R., "Customer value: The next source for competitive advantage", Journal of the Academy of Marketing Science, 25(2), Available at: http://dx.doi.org/10.1007/BF02894350, 1997, pp. 139–153.

Phillip Schrieverhoff
Institute of Product Development, Technische Universität München
Boltzmannstr. 15
Telephone: +49.89.289.15121
Email: schrieverhoff@pe.mw.tum.de
URL:http:// www.pe.mw.tum.de