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# An Integrated Innovation Life Cycle Model for Supply Chain Adaption

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**Abstract:** Supply chains of innovative products are subject to significant change requests during the first phases of the product life cycle. To support the proactive realignment of the supply chain strategy and structure, the early detection of transitions from one life cycle phase to another is crucial. On this account, this paper provides the necessary mathematical foundations based on the life cycle model by Parlings and Klingebiel (2012). The underlying functions and their parameters are derived and analysed to obtain the characteristics that can be used for quantitatively defining phase transitions and early warning areas in an innovation's life cycle.

*Keywords:* Life Cycle, Innovation, Innovation Management, Supply Chain Strategy, Supply Chain Management, Product Strategy, Forecasts, Characteristic Curves

## 1. INTRODUCTION

A radical product innovation is defined by a high degree of novelty combined with its commercial use (Hauschildt and Salomo 2011). Given this economic aspect of radical product innovations, the respective supply chains are subject to rapid change requests. Predominantly, this holds true in early life cycle phases when sales volumes are developing unpredictably and the supplier base is not yet fully established. The supply chain strategy determines the way the supply chain management (SCM) tasks (e.g. procurement, transport of material, distribution) are carried out (Chopra and Meindl 2010). Thus, the supply chain strategy needs to be proactively realigned repeatedly throughout an innovation's life cycle, so that the supply chain can support the economic success of the innovation efficiently (Parlings et al. 2013).

In order to detect transitions of the product innovation from one life cycle phase to another, early warning indicators are needed. Then, the status change within the life cycle of the innovation can be interpreted as one possible trigger for changing supply chain requirements and thus for the realignment of the supply chain strategy.

Nevertheless, different life cycle perspectives, such as sales volume, technology maturity and market hype need to be monitored in order to derive the right supply chain strategy (Linden and Fenn 2003; Parlings and Klingebiel 2012). In response to this challenge, the integrated life cycle model for tracking radical innovations in early life cycle phases has been introduced by Parlings and Klingebiel (2012). This paper presents a mathematical description of this model including objectively assessable facts from different life cycle phases, which support an operationalization for the early detection of phase transitions. The findings are demonstrated by analysing a historic radical innovation (MP 3) as well as a current radical innovation (autonomous cars).

## 2. STATE OF THE ART

This section describes the basics and recent developments in related research topics. In the first section, life cycle models for describing the progress of an innovation are briefly discussed. Following, a supply chain strategy framework for selecting the appropriate supply chain strategy along an innovation's life cycle is introduced. The second section addresses early warning systems and foresight methods.

### 2.1 Innovation life cycles and supply chain strategy adaption

The well-known life cycle model is the "adoption curve" or the "diffusion model" that mirrors the degree of spread of innovations in a social system and thereby considers socioeconomic aspects. Consumers are typically divided in different adoption groups (Innovators, Early Adopters, Early Majority, Late Majortiy, Laggards) depending on the adoption point in time (Rogers 2003). The curve describes the market penetration of the innovation as the percentage of target group adoption over time.

In contrast, Gartner's Hype Cycle (GHC) describes the process of creating a technological innovation as a function of expectations and the perception of innovation over time (Fenn and Raskino 2008). Five essential phases can be identified according to Gartner: the initiation phase of the technology, the phase of inflated expectations, the phase of the low point, the stage of enlightenment and the phase of the productivity level (Linden and Fenn 2003). This model provides significant input for innovation research given its focus on the early stages of a life cycle model.

The technological maturity s-curve or technology life cycle (TLC) places an innovative product along a continuum of the technological progress. Thereby the maturity within a product life cycle is usually divided into four stages of maturity (Fenn and Raskino 2008): The embryonic stage, the stage of development or growth, the stage of adolescence and

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maturity and the stage of aging. The financial performance of an innovation can be assessed on the basis of the profit contribution of the innovation (Eilenberger 2012). From the financial performance perspective, the consideration of the life cycle starts before the market launch of a product, as a significant share of the expenses for research and development occurs prior to the actual diffusion process. Characteristic for the life cycle of innovative products from a financial point of view are negative profit contributions in the early stages of a life cycle. These are, however, in the ideal case, (over-) compensated by a strong sales increase in the diffusion phase (Eilenberger 2012).

The introduced life cycle models illustrate the development of an innovation from different angles and provide relevant insights in order to pursue and understand the development of an innovation, to determine the current status, and to ultimately derive insights for adapting the supply chain. To assign different supply chain strategies to different life cycle phases aspects from all models are relevant. Thus, the four models form the basis of the integrated technological innovation life cycle model developed by Parlings and Klingebiel (2012) shown in Figure 1.

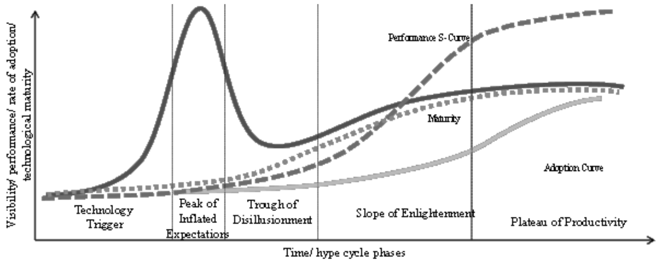
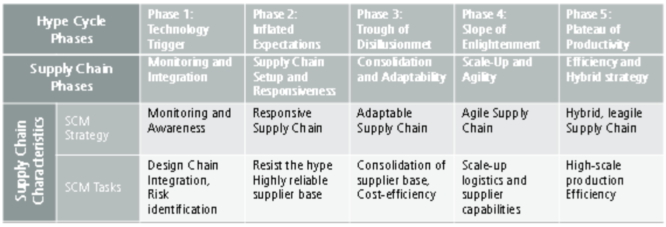


Figure 1: Integrated Technological Innovation Life Cycle Model (Parlings and Klingebiel 2012)

If a phase transition can be identified in the life cycle progress, the supply chain strategy may be adapted in time, thus ensuring the strategic fit (Parlings et al. 2013). For selecting the right supply chain strategy for each life cycle phase, the framework illustrated in Figure 2 has been developed which allows determining the appropriate supply chain strategy for the respective life cycle phase of an innovation (Parlings and Klingebiel 2012).



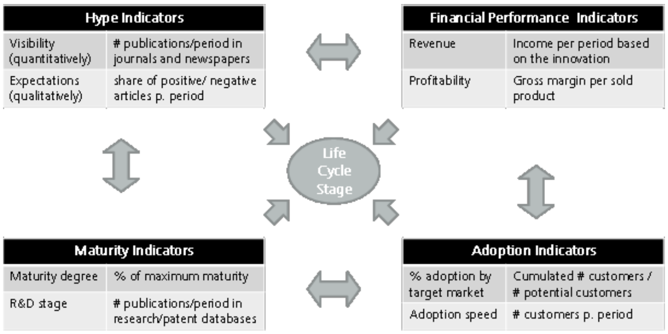
| Hype Cycle Phases | | Phase 1: Technology Trigger | Phase 2: Inflated Expectations | Phase 3: Trough of Disilusionmet | Phase 4: Slope of Enlightenment | Phase 5: Plateau of Productivity |
|---|---|---|---|---|---|---|
| Supply Chain Phases | | Monitoring and Integration | Supply Chain Setup and Responsiveness | Consolidation and Adaptability | Scale-Up and Agility | Efficiency and Hybrid strategy |
| Supply Chain Characteristics | SCM Strategy | Monitoring and Awareness | Responsive Supply Chain | Adaptable Supply Chain | Agile Supply Chain | Hybrid, leagile Supply Chain |
| | SCM Tasks | Design Chain Integration, Risk identification | Resist the hype Highly reliable supplier base | Consolidation of supplier base, Cost-efficiency | Scale-up logistics and supplier capabilities | High-scale production Efficiency |

Figure 2: Framework for mastering innovation from a supply chain perspective (Parlings and Klingebiel 2012)

## 2.2 Early warning systems and foresight methods

Since the development of an innovation's life cycle progress is hardly predictable, the identification of phase transitions in the life cycles of innovative products can be assigned to the research field of foresight methods. Potential risks, opportunities and initiating countermeasures (adaptation of the supply chain) need to be predicted (Loew 2003). This requires the monitoring of short- and medium-term developments of technologies, products and markets (Loew 2003). The most promising type of foresight methods are predictive models based on indicators that monitor information from the macro- and microeconomic environment to create a basis for predicting the further development (Moder 2008).

The balanced scorecard (BSC) approach is a recognized method for the integration of different perspectives and indicators (Kaplan and Norton 1992). The classic BSC approach extends the financial perspective by three further perspectives: customer, internal process, learning and growth perspective (Vinkemeier 2008). Parlings et al. (2013) have shown that an indicator-based BSC approach as a framework for monitoring the life cycle curve of innovations, and in particular, the identification of phase transitions is suitable. Nevertheless, for each life cycle perspective indicators for tracking the progress need to be defined. The resulting innovation life cycle BSC with exemplary indicators for tracking an innovation's life cycle progress is illustrated in Figure 3.



| Hype Indicators | |
|---|---|
| Visibility (quantitatively) | # publications/period in journals and newspapers |
| Expectations (qualitatively) | share of positive/ negative articles p. period |

| Financial Performance Indicators | |
|---|---|
| Revenue | Income per period based on the innovation |
| Profitability | Gross margin per sold product |

| Maturity Indicators | |
|---|---|
| Maturity degree | % of maximum maturity |
| R&D stage | # publications/period in research/patent databases |

| Adoption Indicators | |
|---|---|
| % adoption by target market | Cumulated # customers / # potential customers |
| Adoption speed | # customers p. period |

Figure 3: Innovation Life Cycle BSC (Parlings et al. 2013)

## 2.3 Intermediate Conclusion

For an adjustment of the supply chain strategy to the dynamic needs of the life cycle history of an innovation, early detection of phase transitions by using appropriate monitoring methods is required. An analysis of different methods has shown that indicator systems appear to be promisingly usable. Early detection should be realized by the use of an early warning system, which is based on objectively assessable facts that can e.g. be derived from the Innovation Life Cycle BSC following Parlings et al. (2013). In order to allow the quantitative determination of phase transitions, a mathematical description of the life cycle model is necessary. In the following chapter the integrated life cycle model is mathematical analysed focusing on the mathematical definition of phase transitions.

## 3. FINDINGS

This section first provides the general mathematical description of the curves integrated in the life cycle model. In the second sub-section the critical points that indicate a phase transition are identified and described.

### 3.1 Mathematical description of the life cycles

First, the adoption curve, the performance S-Curve, the TLC, and the GHC are described by mathematical equations. The functional equations of the first three models are all presented as an S-curve within the integrated innovation life cycle model. These models are based on the sigmoid function. The basic form of this function is represented by (Balakrishnan 1992):

$$f(x) = \frac{1}{2a(1+e^{-x})} \quad (1)$$

This basic form of the sigmoid function has to be enhanced by parameters for steepness, jump height and inflection point in order to obtain the most accurate approximation of the curve (see Table 1).

Table 1: Parameters for the expansion of the sigmoid function

| Parameter | Impact |
|---|---|
| α | Steepness |
| γ | Jump height |
| $T_0$ | Inflection point |

The advanced function equation used for the three S-curves is therefore (Martino 2003):

$$f(x) = \frac{\gamma}{(1+e^{-\alpha(x-T_0)})} \qquad (2)$$

The GHC is barely described mathematically in literature. According to Fenn and Raskino (2008), the GHC can best be described by combining two different curves. The first curve is a bell shaped curve that represents the initial enthusiasm and subsequent disillusionment. The second curve is an S-curve which represents the sustainable development of an innovation based on technological its technological maturity (Fenn and Raskino 2008).

The function of the GHC can therefore mathematically be modelled as a combination of a modified version of the witch of Agnesi (Bronshtein et al. 2015) representing the bell-curve-shape of the early life cycle phases and the sigmoid function for the more mature phases. This results in the following mathematical equation for describing the GHC:

$$f(x) = \frac{\kappa}{\left(\left((\varphi x)-\mathrm{T}_{0_2}\right)^2+\omega\right)} + \frac{\gamma}{(1+e^{-\alpha(x-\mathrm{T}_0)})} \qquad (3)$$

The impact of the parameters for fitting the bell-curve-part of the GHC can be found in Table 2.

After having described the general mathematical function of the life cycle curves, the curve functions are analysed to obtain the characteristics that can be used for quantitatively defining phase transitions and early warning areas in an innovation's life cycle.

Table 2: Additional parameters of the GHC function

| Parameter | Impact | Explanation |
|---|---|---|
| κ | Step height | step height of the phase of the peak of inflated expectations in the Hype Cycle |
| ω | Multiplier | influences this step height and operates as a multiplier |
| $\varphi$ | Multiplier | influences the inflection point and can also be seen as a multiplier with the additional condition that it needs to be unequal to zero |
| $T_{0_2}$ | Inflection point | inflection point of the summit of inflated expectations |

### 3.2 Identification of critical points for describing phase transitions

Curve-specific characteristics include the roots of the derivations (including the local minima, maxima and the inflection points) as well as limit values of the function. Furthermore the corresponding tangential equations might be of interest for the early detection of phase transitions.

The identification of the extremes and inflection points seems sufficient for setting up an early warning system in a first step. The limit values of the function as well as the tangential equations will rather be useful for the validation and more detailed analysis of obtained solutions. To obtain the significant points of the curves, common curve analysis is applied.

The adoption curve, the performance S-curve and the TLC are represented by the functional equation (2). It can already be assumed by looking at the graph of the functions in Figure 1 that it does not have any zero or extreme points. For identifying the characteristic points of an S-Curve the derivations of an exemplary S-Curve using the following parameter values are calculated:

$\alpha = 0{,}55,\ \gamma = 1$ and $T_0 = 10{,}5$

$$f(x) = \frac{1}{(1+e^{-0{,}55(x-10{,}5)})} \ (4);\ f'(x) = \frac{0{,}55e^{-0{,}55x+5{,}775}}{(1+e^{-0{,}55x+5{,}775})^2} \ (5)$$

$$f''(x_p) = \frac{0{,}6050\left(e^{-0{,}55x_p+5{,}775}\right)^2}{\left(1+e^{-0{,}55x_p+5{,}775}\right)^3} - \frac{0{,}3025e^{-0{,}55x_p+5{,}775}}{\left(1+e^{-0{,}55x_p+5{,}775}\right)^2} \ (6)$$

$$f'''(x_p) = \frac{0{,}9982\left(e^{-0{,}55x_p+5{,}775}\right)^3}{\left(1+e^{-0{,}55x_p+5{,}775}\right)^4} - \frac{0{,}9982\left(e^{-0{,}55x_p+5{,}775}\right)^2}{\left(1+e^{-0{,}55x_p+5{,}775}\right)^3} + \frac{0{,}1663e^{-0{,}55x_p+5{,}775}}{\left(1+e^{-0{,}55x_p+5{,}775}\right)^2} \ (7)$$

Figure 4 shows the exemplary S-Curve and its derivations. When analysing the derivations the inflection point ($\mathrm{T}_0 = 10{,}5, f(\mathrm{T}_0) = 0{,}5$) can be identified.

The tangential equation t(x) at a given point on an S-Curve is determined by

$$t(x) = \frac{\alpha \cdot \gamma \cdot e^{-\alpha(x_t-T_0)}}{(1+e^{-\alpha(x_t-T_0)})^2}(x-x_t) + \frac{\gamma}{(1+e^{-\alpha(x_t-\mathrm{T}_0)})} \qquad (8)$$

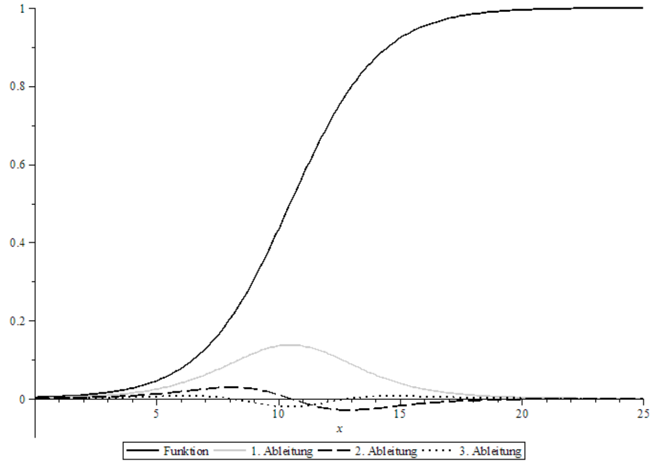


Figure 4: S-Curve with derivations

The GHC is represented by the functional equation (3). This function does not have any zero points. However, it has a local maximum and minimum and three inflexion points.

The tangential equation t(x) at the point $x_t$ is determined by

$$t(x) = \left(\frac{\alpha\cdot\gamma\cdot e^{-\alpha(x_t-T_0)}}{\left(1+e^{-\alpha(x_t-T_0)}\right)^2} - \frac{2\cdot\kappa\cdot\varphi\cdot(\varphi x_t-T_{0_2})}{\left(\left(\varphi x_t-T_{0_2}\right)^2+\omega\right)^2}\right)(x-x_t) +$$

$$\frac{\gamma}{\left(1+e^{-\alpha(x_t-T_0)}\right)} + \frac{\kappa}{\left(\left((\varphi x_t)-T_{0_2}\right)^2+\omega\right)} \quad (9)$$

Figure 5 shows all four curves with indicated significant points (extrema, inflection points) and the tangent at these points. The functions are parameterised to fit the original qualitative life cycle model. Table 3 gives a mapping of the characteristic points to the life cycle phases is given in.

For proactively determining phase changes, early detection areas should be defined on the curve previous to the critical points. Monitoring the early detection area can be achieved by analysing the tangential equation. As the tangential equation approximates more and more the tangential equation at the critical point, the phase transition is imminent.

To apply the formerly derived mathematical model in practice, measurable indicators for tracking the development of an innovation in the respective category are needed. The life cycles can be derived based on various indicators as presented in the Innovation Life Cycle BSC (Figure 3).

For tracking an innovation's progress, the indicator values need to be measured periodically over the life cycle. Thereof the life cycle can be drawn. In order to quantitatively use the findings for the early detection of phase transition, the curve needs to be described mathematically by setting the right parameters indicated in the previous section. Thus, the next step is to find the optimal set of parameters so that the function values approximate the measured values of the indicators best.

The quality of the approximation is measured by the quadratic error which is defined as

$$\sum_{i=1}^{n} |f(x_i) - V_i|^2 \qquad (10)$$

where $V_i$ are the measured values of the indicators in Period i, e.g. number of publications per period in the media and scientific journals for the GHC, and $f(x_i)$ are the approximated function values.

## 4. VALIDATION AND DEMONSTRATION

The first sub-section describes the validation of the analysis results by generating the life cycle model based on historic data. The second sub-section demonstrates the application of the findings to the case of autonomous cars.

### 4.1 Validation

Since the GHC contains the most characteristic points in early life cycle phases and is the most expressive life cycle curve for radical innovations (Parlings and Klingebiel 2012), the curve generation is validated based on a hype cycle example. However, indicators for the others curves should be used in the same way to support the findings of the Hype Cycle monitoring.

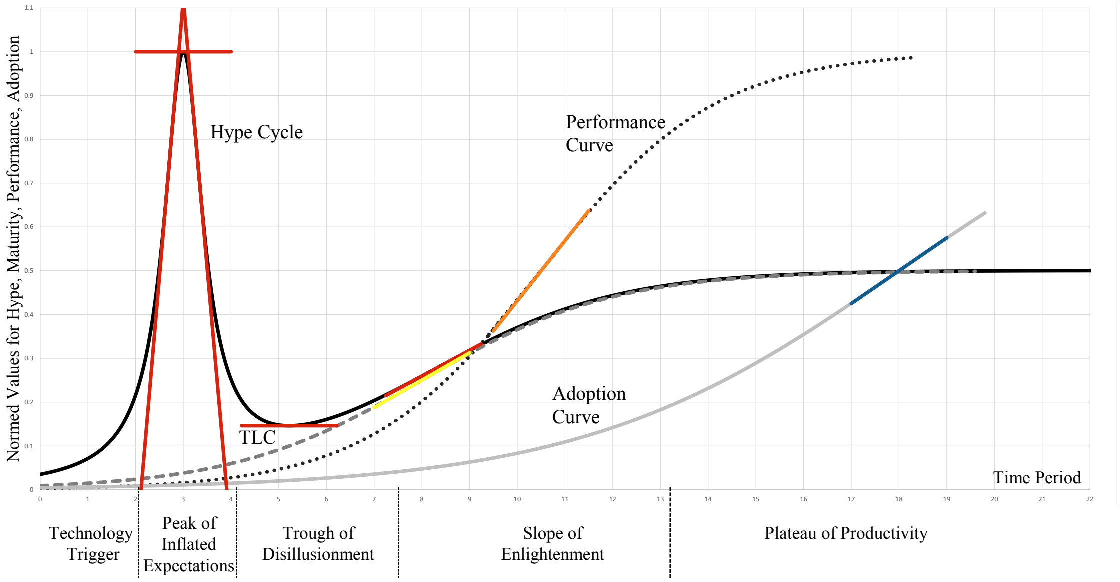


Figure 5: Integrated Technolocial Life Cycle with significant points and their tangents

Table 3: Overview of critical points as indicators for phase transition

| Life Cycle Curve | Phase 1: Technology Trigger | Phase transition | Phase 2: Inflated Expectations | Phase transition | Phase 3: Trough of Disillusionment | Phase transition | Phase 4: Slope of Enlightenment | Phase transition | Phase 5: Plateau of Productivity |
|---|---|---|---|---|---|---|---|---|---|
| Adoption Curve | Stationary slope | | | - | - | - | - | - | Inflection point |
| Performance S-Curve | Stationary slope | - | - | - | - | - | Inflection point | - | Stationary slope |
| Technology Life Cycle | Stationary slope | - | - | - | - | Inflection point | - | - | Stationary slope |
| Gartner's Hype Cycle | - | Inflection point I | Maximum | Inflection point II | Minimum | Inflection point III | - | - | Stationary slope |

The following example, qualitatively obtained from Järvenpää and Mäkinen (2008) is going to illustrate the application of the model in practice. We consider the development of documents mentioning MP3 in a scientific database. Table 4 shows the number of documents.

Table 4: No. of Documents mentioning MP3

| Year | 1998 | 1999 | 2000 | 2001 | 2002 | 2003 | 2004 | 2005 | 2006 | 2007 |
|---|---|---|---|---|---|---|---|---|---|---|
| # documents | 300 | 1300 | 2600 | 1200 | 550 | 560 | 945 | 1300 | 1450 | 1400 |

Now the following optimisation problem has to be solved

$$\text{Min} \quad \sum_{i=1}^{10} |f(x_i) - V_i|^2 \qquad (11)$$

$$s.t. \quad f(x_i) = \frac{\kappa}{\left(\left((\varphi x_i) - T_{0_2}\right)^2 + \omega\right)} + \frac{\gamma}{\left(1 + e^{-\alpha(x_i - T_0)}\right)} \qquad (12)$$

With adjustable parameters $\alpha, \gamma, \kappa, \varphi, \omega$ and the inflection points $T_0$ and $T_{0_2}$

Table 5 presents the optimal values for the parameters obtained by using the Excel Solver. In Table 6 the obtained rounded function values are presented.

Table 5: Results of function approximation

| Parameter | $\kappa$ | $\varphi$ | $\omega$ | $\alpha$ | $T_0$ | $T_{0_2}$ |
|---|---|---|---|---|---|---|
| Opt. Value | 2852.5893 | 1.1190 | 1.0941 | 1.5207 | 5.7678 | 2.1970 |

Table 6: Obtained function values

| Year | 1998 | 1999 | 2000 | 2001 | 2002 | 2003 | 2004 | 2005 | 2006 | 2007 |
|---|---|---|---|---|---|---|---|---|---|---|
| x Value | 0 | 1 | 2 | 3 | 4 | 5 | 6 | 7 | 8 | 9 |
| Function value f(x) | 482 | 1265 | 2608 | 1190 | 543 | 557 | 954 | 1299 | 1413 | 1433 |

Figure 6 shows the approximated function values compared to the measured values. As it can be seen it is a good approximation to represents the measured data which makes it possible to determine critical points to indicate phase transitions. The next subsection will demonstrate the application of the model as an early warning system in a general example.

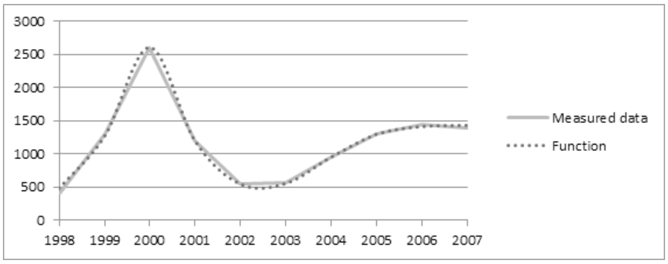


Figure 6: Approximated function values and measured values

### 4.2 An Application Case – Autonomous Cars

The findings are now applied to the innovation case of autonomous cars using the indicators and data from various sources. Autonomous cars are a currently developing hype technology. The latest Gartner reports state that autonomous cars are in the second hype phase (Inflated Expectations).

Bibliometric data on autonomous cars for the representation of the hype cycle has been obtained by counting the number of publications in the New Your Times covering the subject of autonomous cars. The date range was set from January 1st to December 31st for each year. For displaying the maturity of the innovation using the technology life cycle model, the cumulative number of patents in the USPTO (United States Patent and Trademark Office) database has been evaluated. Given the early stages of the autonomous vehicle technology life cycle, no data related to the performance and adoption has been obtained. Table 7 shows the number of mentions in NYT articles per year as well as the cumulated number of patents on autonomous cars in the USPTO.

Table 7: Number of NYT articles covering autonomous cars

| Year | 2004 | 2005 | 2006 | 2007 | 2008 | 2009 | 2010 | 2011 | 2012 | 2013 | 2014 | 2015 |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| # docs per year | 1 | 3 | 3 | 7 | 2 | 4 | 4 | 9 | 25 | 52 | 88 | 224* |
| Cum. # of USPTO patents | 1 | 1 | 1 | 2 | 3 | 5 | 6 | 10 | 12 | 20 | 34 | |

* 2015 value extrapolated, 159 documents on NYT.com until 28.09.2015

The approximation of the function for both curves returns the parameter values listed in Table 8.

Table 8: Results of function approximation (rounded)

| Parameter | $\kappa$ | $\varphi$ | $\omega$ | $\alpha$ | $T_0$ | $T_{0_2}$ |
|---|---|---|---|---|---|---|
| GHC | 1.9500 | 0.0765 | 0.0067 | 1.0000 | 22.9998 | 0.8861 |
| TLC | - | - | - | 0.4384 | 20.4058 | - |

Figure 7 shows the approximated function values compared to the measured values. Based on the approximation using the mathematical functions introduced in section 3, it can be deduced that the technology is technologically still in an embryonal status. The hype will rise another year before entering the trough of disillusionment until the end of this decade. With the technology maturing more and more during the next decade, the slope of enlightenment will be climbed within the second half of the next decade.

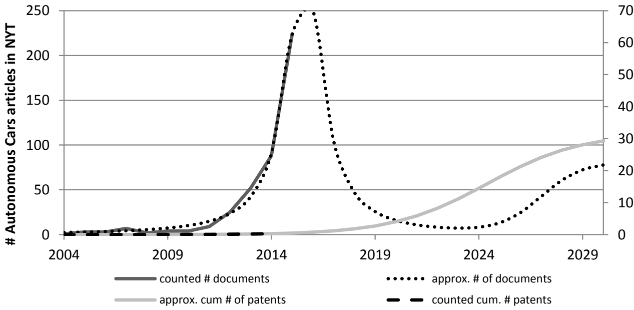


Figure 7: Projection of GHC and TLC for autonomous cars

Thus, supply chains should prepare to reduce the complexity and the cost in the next years in order to contribute surviving the trough as no significant sales are expected within the next years (Parlings and Klingebiel 2014). Further tracking the innovation's progress in the next years will help to anticipate the entrance to the slope of enlightenment.

## 5. CONCLUSION AND OUTLOOK

This paper has focused on the mathematical description of the integrated technological innovation life cycle model. The findings are a first step for the operationalisation of the life cycle model. The quantitative monitoring and analysis of an innovation's life cycle progress is crucial to the prospective development of an early warning system for the detection of phase transitions in order to timely adapt a supply chain's strategy and structure.

The approach to predict phase transitions demonstrated in this paper implies the approximation of the life cycle curves based on historic data. The demonstration results show that by following this approach the life cycle phases can roughly be predicted. Nevertheless, only the next one or two phases can be predicted reliably as the graph changes with further data input. The sensitivity of the parameters is an important field of further research.

Furthermore, this requires the availability of historic data from previous periods and thus implies that the innovation should have left its earliest phase. To achieve a more accurate approximation following the early hype, the negative turn of the function's slope needs to be reached. And for the most precise prediction of an innovation's phase transitions, the measuring periods for the underlying indicators should be shorter, e.g. at least based on months.

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