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Modeling and Analyzing Cycle Networks in Product-Service System Development using System Dynamics

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Abstract

The development of product-service systems is affected by a large number of influences. These influences often show a cyclic character. The management of these cyclic influences reveals great potential for improving the product-service system development process. Knowledge about influences and their interdependencies supports the prediction of future changes and is highly valuable for planning. A core challenge is the high degree of dependencies between the different cycles.

In this work, we show how to model and analyze cycles with interdependencies using system dynamics by extending a case study of former research. A previously developed cycle network is adjusted and a system dynamics model of the resulting cycles and their interdependencies is implemented. This enables a mathematical analysis and comprehension of the cycles within the network, supporting the understanding of the future behavior of cyclic influences and anticipating their potential effects. We introduce a replacement for the sigmoid function, which is frequently used to model cycles, but not suitable to include dependencies. The results emphasize the feasibility and benefits of a quantitative analysis. Though the model needs to be adjusted for specific use cases, the created network can serve as a framework for analyzing the development process of product-service systems and support deeper understanding of the interdisciplinary interdependencies.

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Keywords: Cycle Management, Cyclic Influences, Dynamic Simulation

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1. Introduction

Product-service systems (PSS) are becoming an increasingly important concept in industry and research, because these integrated offerings, consisting of tangible products and intangible services, can more precisely fulfill customer needs and may lead to economic advantages in competition [1–3]. In addition to well-known aspects like shortened innovation cycles and high pressure concerning time, cost, and competition, the integration of products and services in one system further complicates the development due to an increased interdisciplinary character [4].

Companies must continuously adapt their products, processes and production within the product life cycle [5,6]. The adaptation and development of PSS is significantly affected by numerous internal and external influences (see [7]) and high uncertainties of future requirements [8]. These influences often show a cyclic character which means they have a timely or structurally reoccurring pattern [9,10]. In the context of these aspects, companies have to optimize their processes to improve their competitiveness by integrating internal (i.e., engineering change cycles and team building processes) and external (i.e., government- and customer-related demands) cycles in their prevision [4].

However, the anticipation of these internal and external cycles is challenging due to their complex dynamic behavior [9,10] as well as their mutual dependencies and influences [4]. The unawareness and lack of manageability of these cycles lead to challenges that are addressed by cycle management. This contribution models the behavior and the dependencies of cycles using system dynamics to support decision-making in development. We extend the previously developed qualitative approach [4] by quantitative means to compensate the shortcomings. The original approach in [4] has a high level perspective on the system and, due to the qualitative analysis, no tangible and hardly traceable interdependencies. The presented quantitative analysis enables the validation of the influences' implications, which are evaluated and compared in two scenarios.

The sigmoid function previously used to describe certain cycles [11–13] is replaced by a function which allows to include interdependencies. For constant influences, the shape of this function is also an S-shape, similar to the sigmoid function.

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The next section revises the fundamentals of cycle networks (multiple interconnected cycles), particularly in the context of PSS and their modeling on a general level. In Section 3, the cycle network from [4] is adapted and the mathematical model is presented. Finally, the simulation results and the benefits of the introduced system dynamics model will be presented and analyzed in Section 4, before passing to the conclusion in Section 5.

2. Background

2.1. Cycles and their interdependencies

A cycle is a reoccurring (temporally or structurally) pattern that can be divided into phases and is characterized by repetition, duration, trigger and effects [10]. According to [10], cycles can be further detailed by defined characteristics:

- A cyclic object describes the regarded patterns.
- The predictability describes the foresighted estimation.
- The controllability describes the intensity of the company's influence on a cycle.
- The type of management defines the way how to deal with cycles (reactive or proactive).
- The objects of managements describe which parts of the cyclic object are handled.
- The interrelation describes the cross-linking with other cycles.

In literature multiple categorizations of cycles are differentiated. For instance, some cycles can easily be quantified while others cannot, e.g., due to a lack of data [14]. Consequently, the latter can only be modeled in a qualitative way [14]. Cycles can be distinguished, regarding the perspective (internal and external) [4,15,16] as well as their addressed level [10]. Micro level cycles exemplary describe patterns on the process activity level and macro level cycles on innovation process level, like technology maturity changes.

In the context of the collaborative research center 768, a cycle network was developed over several years which is presented in [4]. Since this network builds the basis for this contribution, the following focuses on the description of this cycle network. The network is illustrated as a graph model that consists of eight top level cycles which are again subdivided into subnetworks. Each cycle is represented as a node while dependencies are represented by edges. The edges link nodes within a subnetwork but also nodes beyond the subnetwork, independently of their hierarchical level. The dependencies are further detailed by a short description (i.e., triggers, provides, etc.). The eight top level cycles are the development cycle, engineering change cycle, manufacturing structure cycle, requirement and planning cycle, team process cycle, PSS usage cycle, user acceptance cycle, and user integration cycle. Each of the cycles is further detailed by a description, its behavior, sub-cycles, and interdependencies. Another cycle network is presented in the context of manufacturing planning in [12]. This network consists of six cycles with a clear focus on manufacturing: product life cycle, manufacturing technology life cycle, engineering change cycle, manufacturing change cycle, manufacturing resource cycle, and manufacturing structure cycle. Nevertheless, it is again represented as a graph model consisting of nodes (cycles with behavior) and edges (interdependencies).

Despite the gained knowledge about cycles, their time dependent behavior and their interdependencies require a dynamic modeling of the network [12]. Moreover, Ref [4] and [14] also ask for a quantified model and analysis of cycle networks. The previously mentioned network in the context of manufacturing planning was quantitatively implemented and indicates a general validity and mathematical applicability of the system dynamics approach in the context of dynamic cycle modeling [12]. System dynamics is a methodology to analyze and simulate complex dynamic systems [17]. Quantitative system dynamics uses stocks and flows to describe qualitative dependencies, e.g., reinforcing or balancing loops [4].

2.2. Modeling and simulating cycle networks

In order to transition from systems thinking and soft operations research to a dynamical network model, the qualitative cycle network needs to be described with additional quantitative information [17]. In addition to the overall behavior and appearance of each cycle, also the interconnections and the time scales, as well as the behavior on certain events need to be clarified and translated into a mathematical representation, appropriate for simulation. The ability to simulate scenarios helps validate assumptions, compare different strategies or carry out sensitivity analyses [12].

In the context of simulating cycle networks, we differentiate between cycles that exist during all times with a periodic behavior and cycles that occur and run out at certain points in time. The latter often require a triggering event starting the cycle, followed by a continuous development in the form of differential equations and eventually a finishing event or running out of the cycle.

While in previous works the sigmoid function is often used to describe the dynamic behavior [11–13] of certain cycles, we found the resulting behavior extremely sensitive to the initial value. Moreover the sigmoid function does not have an input for external signals and is thus only suited to describe cycles without interdependencies. Instead, we propose to use an all-pole second order transfer function with unit gain, used frequently in engineering, e.g., feedback control systems [18]. The resulting shape for a constant input is an S-shape which can be intuitively described by a time constant and a damping factor, defining the speed of change as well as the transient behavior of the dynamics in a decoupled manner. An example of a system which can be modeled by a second order transfer function is a linear mass-spring-damper system. Assuming an input signal u and output signal y, the mathematical description of such a system, with time constant T and damping factor D is

$$T^2\ddot{y} + 2TD\dot{y} + y = u. \tag{1}$$

The time constant T is related to the natural frequency ω_n of the system by the relation $T = \frac{1}{\omega_n}$. Methods for the analysis of equation (1) can be found in basic control theory literature, e.g., [18]. Equation (1) describes how the output y changes with respect to the current input u . To compute the time course of y, one usually uses numerical integration, e.g., the forward Euler method. For further references to this second order transfer function, we will use the abbreviation TF2. The input signal u can originate e.g., from a different cycle, making the TF2 suited to model influences and dependencies between cycles.

3. Methodology

3.1. Procedure and methodology

In the context of the manufacturing planning network introduced in Section 2.1, a framework for computing dynamic cycle networks was developed. The general methodology suggests three steps to define a cycle network [12]:

1. Selection of change-relevant influences.
2. Description of each influence's cyclic behavior.
3. Identification of plausible interrelationships between influences.

This contribution's methodology basically follows these three steps. Firstly, the selection of relevant influence cycles (1) is based on the previously developed cycle network that was introduced in Section 2.1. A hypothetical case from [4] is taken up and serves as input to select specific cycles from the entire network. Consequently, they define the relevant cycles in the context of this study. Due to the complexity and lack of information, some assumptions and simplifications are applied.

The description of each involved cycle (2) is based on prior research [4,12]. The hypothetical case compares two scenarios that are independently modeled and analyzed. On the one hand, qualitative descriptions and schematic behaviors of the major cycles are provided [4] and on the other hand mathematical descriptions of selected cycles are proposed in [12]. We relied on the qualitative descriptions and developed our own mathematical model with reasons explained in Section 3.3. The interrelations between the selected cycles (3) are again chosen according to the original cycle networks [4,12].

3.2. Description of the cycle network

Our use case is a hypothetical case based on [4] that describes the implementation of an upcoming requirement in an already existing PSS. An exemplary assumption is that the Manufacturing Structure Cycle is not up to date, but still capable to continue production of the current system (for more details see [4]). The question of the scenario is whether a Change Cycle should be triggered immediately (scenario 1) or whether the requirement should be implemented in terms of the next upcoming Development Cycle (scenario 2). The resulting cycle network for both scenarios is shown in Figure 1. Ten cycles and their interrelations depending on the scenarios are described. The original network [4] contains more elements, but for reasons of lacking information and comprehensibility, the network is reduced and simplified. For the specification of the cycles and the interconnections, the descriptions given in [4,12] are combined. The ten considered cycles (see Figure 1) are described in the following:

The Planning Cycle (PC) (1) schedules the implementation of requirements. It consequently triggers Engineering Change Cycles (ECC) and Development Cycles (DC). An Engineering Change Cycle (2) describes this requirement implementation outside of Development Cycles. This PSS modification causes changes in the manufacturing structure and triggers a Team Cycle (TC). Similarly, the Manufacturing Change Cycle (MCC) (3) defines the implementation of changes for manufacturing resources or structures and causes Manufacturing Structure Cycles (MSC) (4) that develop the production system structure's suitability for the current situation. Engineering Changes cause Team Cycles (4) that are mostly interdisciplinary in the PSS context. They describe the team performance and have a major influence on the Development Cycle. The Development Cycle (6) is characterized by the implemented requirements over time and triggered by the Planning Cycle. Within the Development Cycle, the Technology Cycle (TecC) (7) is triggered. New Technologies increase the PSS demand. The PSS Demand Cycle (DemandC) (8) is strongly influenced by the user acceptance and describes the current demand. In conflict of demand and PSS availability, which is described by the PSS Stock Cycle (StockC) (9), stands the PSS Usage Cycle (UsageC) (10). It represents the occupancy rate of the PSS over its life cycle.

In their qualitative analysis, the authors of [4] came to the conclusion that scenario 2 would be the better option to maintain the user acceptance high in a long term, so the demand for usage. In the following analysis of the model this assumption is validated quantitatively. Hence, the suitability and feasibility of the mathematical approach is verified.

3.3. Simulation model of the dynamic cycle network

For the two example scenarios under consideration, the mathematical equations are described in this section. As a general notation t describes the time in years, and $y_\mathrm{c}(t)$ represents a numerical value referring to the current state of cycle c. $u_\mathrm{c}(t)$ is an input value that affects the target state of the cycle. The numerical values of the parameters describing the system were initiated and adjusted by hand to depict reasonable scenarios, they must be adjusted for real world cases.

Scenario 1 contains the PC, ECC, TC, DC, MSC, StockC, DemandC and UsageC (cf. Figure 1).

The PC is modeled to trigger an ECC every 15 years, starting at year 5. The ECC value y_ECC jumps to 1, signaling an ongoing cycle, and triggers a TC and the related DC. The ECC is finished after the DC reaches a value above 0.99 and the value then returns to 0.

The value of the TC y_TC describes a normalized team performance. It is evolving over time, according to equation (1) with $T = 1$ and $D = 1$. The input to the TC u_TC is a random signal following a uniform distribution of values between 0 and 1. This input can be interpreted as the teams' motivation changing slightly from day to day. With the end of the ECC, the TC also ends.

The value y_DC referencing to the DC describes the progress of the development. The progress is carried out by the team, thus the TC dictates the change in the DC value. The DC value is modeled as the integral of the team performance over the respective cycle. Thus the development will progress faster if the team is working efficiently. According to [4], the development can also be hindered by randomly appearing problems, e.g., new requirements. These disturbances spawn randomly during an ECC and have a random, but short duration. With each active disturbance, y_DC is decreased. The final DC model,

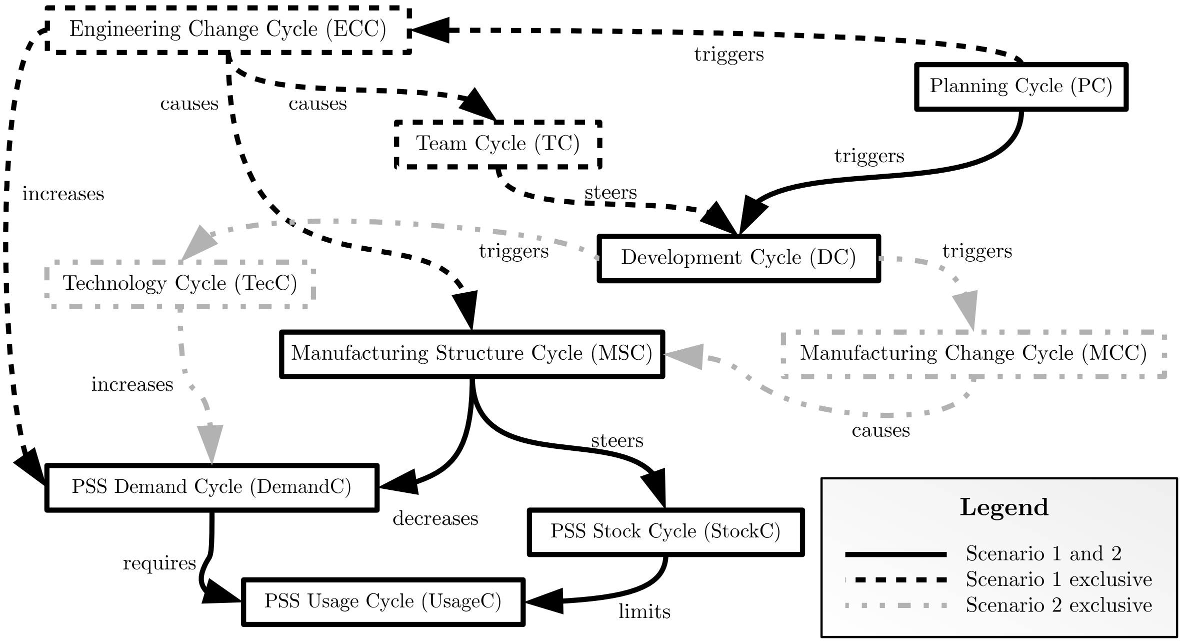

Fig. 1. Cycle Network showing qualitative dependencies between cycles. Abbreviations for cycles used in this paper are also given in brackets.

with the cycle assumed to have started at t_0 and the number of active disturbances at time t being $N_{\text{dist}}(t)$, is:

$$y_{\text{DC}}(t) = \int_{t_0}^{t} 0.4 y_{\text{TC}}(\tau) - 0.2 N_{\text{dist}}(\tau) d\tau. \tag{2}$$

Moreover, the value of the DC cannot decrease below 0 and is clipped to have a minimum of 0 in the case of early disturbances.

The MSC is modeled as a periodic, always existent cycle, repeating itself every 20 years. Its starts at a value $y_{\text{MSC}} = 0.8$ and decreases at a constant rate of 0.02 per year, until the manufacturing structure is modernized after 15 years of usage, rendering the MSC to a value of 0.5 for 5 years, and then starting at 0.8 again.

The StockC value is following the MSC value in a smooth manner with a certain delay. The underlying equation is a TF2 with $T = 0.5$ and $D = 1.0$ and input $u_{\text{StockC}} = y_{\text{MSC}}$.

The demand is described by a TF2 with $T = 3.0$, $D = 1.0$ and constant input $u_{\text{DemandC}} = 0.5$, causing it to converge to this value. The demand value is reset when the ECC is finished to $y_{\text{DemandC}} = 0.9$, describing an increased interest after an ECC has finished.

Finally the usage is modeled as the minimum of the available stock and the current demand:

$$y_{\text{UsageC}}(t) = \min(y_{\text{StockC}}(t), y_{\text{DemandC}}(t)). \tag{3}$$

Scenario 2 contains the MCC, DC, TecC, MSC, DemandC, StockC and UsageC (cf. Figure 1).

The StockC and UsageC are modeled in the same way as in the first scenario. For the demand, the only difference is the reset to $y_{\text{DemandC}} = 0.9$ being triggered by a finishing MCC.

The PC is triggering an MCC every 20 years, starting at year 5. The MCC on its side triggers a TecC and a related DC. The MCC value is 1 if an MCC exists and returns to 0 when it is finished. An MCC is finished if both the underlying TecC and DC reach a value above 0.99.

The DC is described by a TF2 with $T = 1.0$, $D = 1.0$ and constant input $u_{\text{DC}} = 1$. The related TecC is a TF2 with $T = 0.5$, $D = 1.0$, and the input depending on the DC. With a probability y_{DC}, the input u_{PTC} is 0.2 above its current value, and with probability $1 - y_{\text{DC}}$, the input is 0.2 below its current value. Thus to conclude:

$$u_{TecC} = \begin{cases} y_{TecC} + 0.2 & \text{with prob. } y_{\text{DC}} \\ y_{TecC} - 0.2 & \text{with prob. } 1 - y_{\text{DC}} \end{cases} \tag{4}$$

This relation expresses the idea of a more probable successful technology development in more advanced stages of the development cycle.

The MSC is reset with each finishing MCC to a value of $y_{\text{MSC}} = 0.8$, then decreases with a rate of 0.02 per year until the next MCC is triggered, where the value of the MSC is constant at $y_{\text{MSC}} = 0.5$.

4. Results and interpretation

The simulation results for the cycle network described in Section 3.3 are shown for scenario 1 in Figure 2 and for scenario 2 in Figure 3 respectively.

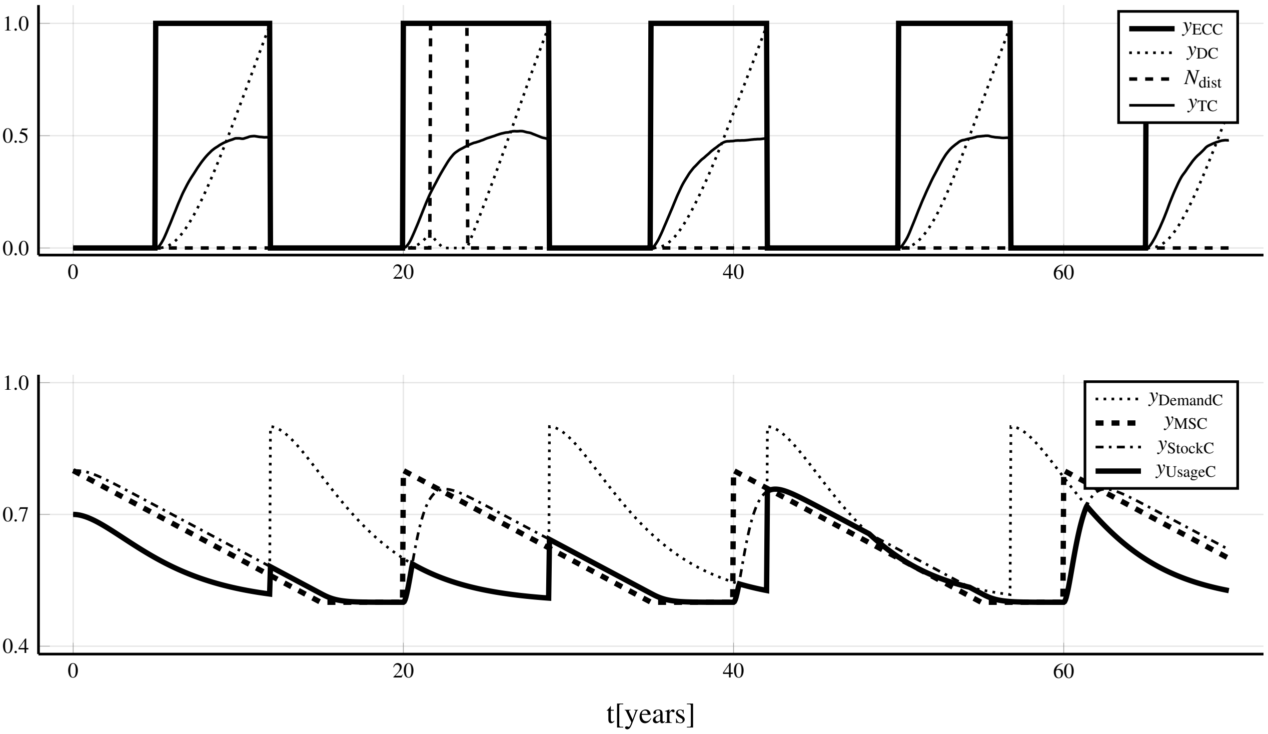

Fig. 2. Simulation results for scenario 1. The top sub-figure shows the ECC with its related DC and TC. During the second ECC, a disturbance is appearing, delaying the DC and therefore the whole ECC. In the bottom sub-figure, MSC, demand and usage are presented. The demand and stock are not synchronized well, which can be seen during the first two ECC cycles where the usage stays exceptionally low.

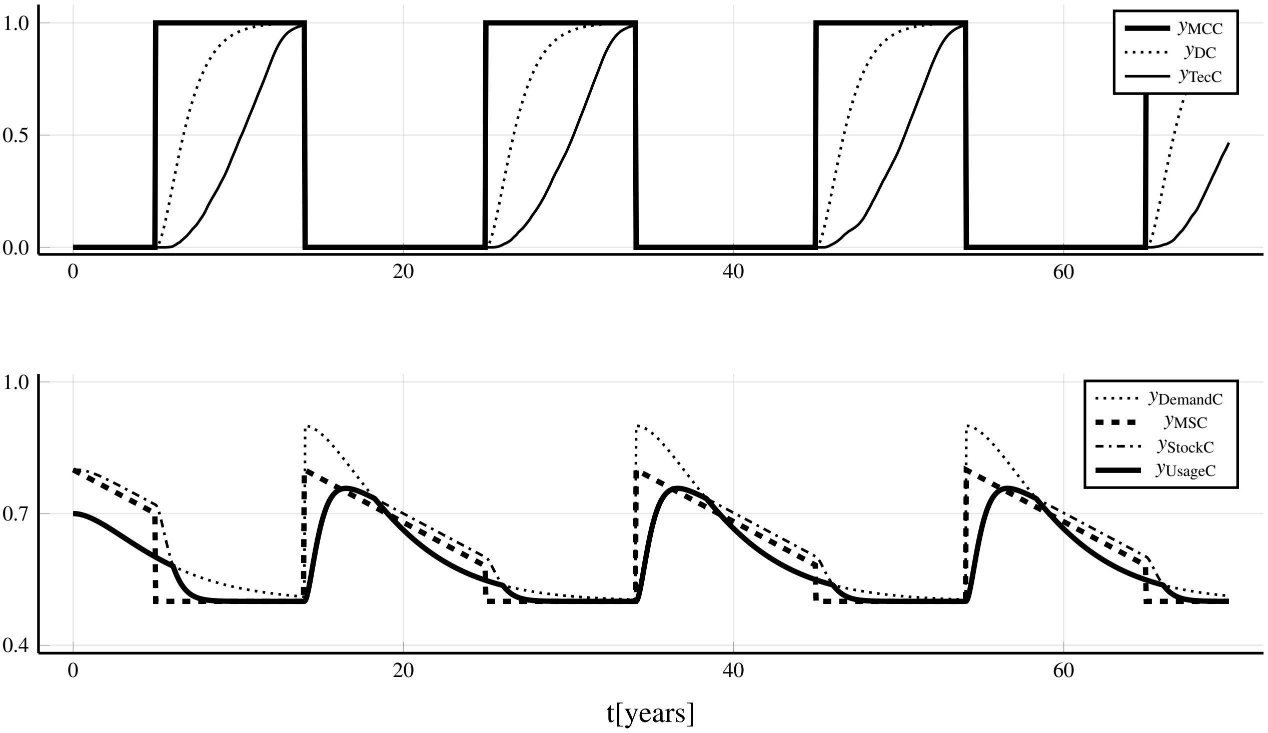

Fig. 3. Simulation results for scenario 2. The top sub-figure depicts the occurring MCC's with their respective DC and TecC's. While a small amount of stochasticity exists in the TecC, the behavior is very periodic and predictable. Regarding the bottom sub-figure, one can observe that the synchronization of the stock and demand is assured, leading to a cyclical and improved usage, compared to scenario 1.

In scenario 1, compared to scenario 2, the development cycles are finished faster and triggered more often, while the manufacturing structure cycle has the same period, but with less downtime. This results from the decision to immediately trigger the engineering changes in case of need. However, the usage is lower in scenario 1. While the changes are implemented faster and more often, they are not synchronized with the manufacturing structure cycle. This can lead to an inefficient manufacturing structure while the demand is high, resulting in an unsatisfied demand followed by a good manufacturing performance but little demand later on.

In scenario 2, the development cycle is started with the manufacturing change cycle, leading to a synchronization of high demand with a high stock, resulting in an increased usage compared to scenario one. For this scenario, the overall demand is lower over the considered time period, but since the demand is synchronized with the manufacturing, the overall usage is higher.

Basically, the simulation results validate the estimations of [4]. However, the results depend on the different time scales of the development cycles and on the defined planning cycles, dictating the period between triggers. Therefore, the time scales need to be adjusted for specific use cases. The dependence on the mentioned parameters becomes clear and can be visualized once a system dynamics model has been created. The qualitative cycle description of [4], however, is not sufficient to recognize or analyze this information. This justifies the assumption that qualitative models of cycles are limited when analyzing cycle networks, as their interconnections, which might act on different time scales, can lead to dynamics that cannot be predicted easily.

5. Conclusion

In the context of product-service system development, the management of cycles is becoming an increasingly important aspect to understand and improve processes and the decision-making. This study has taken up a previously developed cycle network and extends the qualitative description and analysis by quantitative means. The application in a hypothetical case confirms the suitability of system dynamics for computing and analyzing cycle networks. The quantitative analysis shows benefits in traceability compared to the qualitative analysis, especially with regards to interconnections, and clarifies the need for cycle synchronization. In ongoing studies the implementation of real world data could give indications about necessary data input in terms of quality and quantity. Furthermore, it could reveal how beneficial the simulation of the inter cycle connections is in practice. The model could also be used for sensitivity analyses in further works.

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References

[1] Tukker, A.. Eight types of product–service system: eight ways to sustainability? experiences from suspronet. Business strategy and the environment 2004;13(4):246–260.

[2] Baines, T.S., Lightfoot, H.W., Evans, S., Neely, A., Greenough, R., Peppard, J., et al. State-of-the-art in product-service systems. Proceedings of the Institution of Mechanical Engineers, Part B: journal of engineering manufacture 2007;221(10):1543–1552.

[3] Goedkoop, M., van Halen, C., te Riele, H., Rommens, P.. Product service systems, ecological and economic basics. 1999.

[4] Grüneisen, P., Stahl, B., Kasperek, D., Maurer, M., Lohmann, B.. Qualitative system dynamics cycle network of the innovation process of product service systems. Procedia CIRP 2015;30:120–125.

[5] Huang, G., Mak, K.. Current practices of engineering change management in uk manufacturing industries. International Journal of Operations & Production Management 1999;19(1):21–37.

[6] Dengler, C., Schönmann, A., Lohmann, B., Reinhart, G.. Cycle-oriented evaluation of production technologies: Extending the model of the production cycle. Procedia CIRP 2017;61:493–498.

[7] Kammerl, D., Echle, S., Mörtl, M.. Gathering and analysing external influences on the product design-a case study. In: DS 87-6 Proceedings of the 21st International Conference on Engineering Design (ICED 17) Vol 6: Design Information and Knowledge, Vancouver, Canada, 21-25.08. 2017. 2017, p. 169–178.

[8] ElMaraghy, H., Azab, A., Schuh, G., Pulz, C.. Managing variations in products, processes and manufacturing systems. CIRP annals 2009;58(1):441–446.

[9] Langer, S., Knoblinger, C., Lindemann, U., et al. Analysis of dynamic changes and iterations in the development process of an electrically powered go-kart. In: DS 60: Proceedings of DESIGN 2010, the 11th International Design Conference, Dubrovnik, Croatia. 2010, p. 307–318.

[10] Schenkl, S.A., Behncke, F.G., Hepperle, C., Langer, S., Lindemann, U.. Managing cycles of innovation processes of product-service systems. In: Systems, Man, and Cybernetics (SMC), 2013 IEEE International Conference on. IEEE; 2013, p. 918–923.

[11] Greitemann, J., Stahl, B., Michels, N., Lohmann, B., Reinhart, G.. Quantitative model of the technology lifecycle for forecasting the maturity of manufacturing technologies. In: Management of Innovation and Technology (ICMIT), 2014 IEEE International Conference on. IEEE; 2014, p. 290–294.

[12] Plehn, C., Koch, J., Diepold, K., Stahl, B., Lohman, B., Reinhart, G., et al. Modeling and analyzing dynamic cycle networks for manufacturing planning. Procedia CIRP 2015;28:149–154.

[13] Andersen, B.. The hunt for s-shaped growth paths in technological innovation: a patent study. Journal of evolutionary economics 1999;9(4):487–526.

[14] Stahl, B., Diepold, K.J., Pohl, J., Greitemann, J., Plehn, C., Koch, J., et al. Modeling cyclic interactions within a production environment using transition adaptive recurrent fuzzy systems. IFAC Proceedings Volumes 2013;46(9):1979–1984.

[15] Langer, S.F., Lindemann, U., et al. Managing cycles in development processes-analysis and classification of external context factors. In: DS 58-1: Proceedings of ICED 09, the 17th International Conference on Engineering Design, Vol. 1, Design Processes, Palo Alto, CA, USA, 24.-27.08. 2009. 2009, p. 539–550.

[16] Schönmann, A., Ulverich, M., Intra, C., Reinhart, G.. Considering external and internal cycles of a manufacturer for planning and evaluating production technologies. Procedia CIRP 2016;55:47–52.

[17] Forrester, J.W.. System dynamics, systems thinking, and soft or. System dynamics review 1994;10(2-3):245–256.

[18] d’Andréa Novel, B., Lara, M.D.. Control Theory for Engineers. Springer Berlin Heidelberg; 2013. doi:10.1007/978-3-642-34324-7.