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Abstract

Simulation models are important instruments for analysing business systems. They are classified into time-discrete and time-continuous simulation models, for example Discrete Event Systems (DEVS) or System Dynamics (SD) models. These special models are particularly suitable to analyse subsystems of a business system with either time-discrete or time-continuous behaviour. However, in general they are not appropriate to analyse a business system which shows time-discrete and time-continuous behaviour simultaneously. Analysing business systems with time-discrete and time-continuous behaviour with isolated submodels and consolidating the findings of these analyses afterwards may lead to redundancy and consistency problems. In this paper an approach for developing hybrid simulation models, which exhibit time-discrete and time-continuous behaviour, is presented. The hybrid simulation models contain DEVS and SD simulation submodels that are coupled. The approach introduces a structural model of business systems that consists of several control layers with time-discrete or time-continuous behaviour, as well as a modelling approach for integrating DEVS and SD submodels by coupling mechanisms. Finally, an investigation of a market case illustrates the use of the presented approach.

Keywords: business systems, modelling and analysis of business systems, Discrete Event Systems (DEVS), System Dynamics (SD), hybrid simulation, coupling mechanisms.

1 INTRODUCTION AND PROBLEM SETTING

Investigations of complex dynamical business systems and their environments are conducted by designing models, which represent the whole or only parts of these business systems (for instance models of business processes) firstly, and by analysing these models afterwards. The power of simulation models is the ability to mimic the dynamics of systems that feature a complex structure and behaviour. Simulation models are classified into time-continuous and time-discrete models depending on their time scale.

With regard to the degree of abstraction of investigations and according to the general economic theory (Mankiw 2008) we distinguish between *micro* and *macro analyses of business systems* in the following. A micro analysis is an investigation of the behaviour of components of business systems *over a (relatively) short period of time* by using time-discrete and in some cases time-continuous simulation models (i.e. in the production area). We denote micro analysis models as *micro simulation models*. The nature of a *macro analysis* is the investigation of aggregated variables of business system components or of an aggregation of business system components *over a long period of time* by using time-continuous simulation models (i.e. temporal behaviour of model variables, such as sales, demand for a product in a specific market or stocks). In the following, we refer to models used for macro analyses of business systems as *macro simulation models*.

With micro and macro analyses conducted, different investigation objectives are addressed. Micro analyses are mainly used for investigating cycle times of individual objects or resource capacities needed for carrying out individual activities. In contrast, objectives of macro analyses of business systems are directed towards the determination of long-term time-continuous behaviour of model variables as well as to the analysis of the stability of business systems.

Until today, *integrated micro and macro analyses of business systems* with integrated micro and macro models have not been used extensively (Lee & Cho & Kim 2002, Rabelo & Helal & Jones & Hyeung-Sik 2005, Suchan 2009), among other reasons, due to the lack of suitable approaches (cf. Section 2). According to current modelling practice, micro and macro models of business systems are constructed and analysed separately. Findings of micro analyses, if applicable, are used in macro analyses and vice versa, macro analyses affect the construction and execution of micro analyses. However, the related models are not integrated. Simulation experiments are carried out separately from each other. This approach shows some problems that can occur (p_1 to p_5) from the *perspective of the model theory* (Ferstl 1992, Halloun 2006):

- *Model consistency (p_1)*: If micro and macro simulation models overlap with regards to the modelled real world (the business system), the consistency of both models needs to be assured. The sales behaviour in a macro analysis has to be consistent with the sales process in a corresponding micro analysis, for example.
- *Redundancy of model components (p_2)*: Another consequence of overlapping micro and macro simulation models are the redundant model variables, which lead to increased modelling efforts and inconsistencies.
- *Connection of model components (p_3)*: By using isolated micro and macro models, relationships between model variables of these models are not considered sufficiently. Findings of macro models are not applied directly and automatically to micro models and vice versa.
- *Decomposition of investigation objectives (p_4)*: Complex investigation objectives, which can not solely be pursued with micro or macro analyses, have to be decomposed into less complex objectives and investigated separately. Dependencies among objectives lead to increased investigation efforts.
- *Modelling and model investigation effort (p_5)*: Isolated modelling and isolated investigations of micro and macro models lead to redundant modelling and investigation activities.

In order to overcome these problems, we propose an approach of a hybrid simulation system that consists of time-discrete and time-continuous simulation subsystems. The approach is suitable for *constructing integrated macro and micro simulation models of business systems* and for *conducting integrated macro and micro analyses of business systems*. We use the System Dynamics (SD) Methodology (Forrester 1969, Sterman 2000) for the modelling of time-continuous subsystems and the Discrete Event Systems (DEVS) simulation modelling approach (Schriber & Brunner 2007) for the modelling of time-discrete subsystems. The simulation approaches SD as well as DEVS are well known and well-investigated in research (see i.e. the *Proceedings of the Winter Simulation Conferences* or the *SD Review*). To tackle the problems p_1 to p_5, we decompose our research objective into the following research questions:

a) ***Modelling of business systems:*** *Which subsystems of a business system should be represented by a time-continuous simulation submodel, and which by a time-discrete submodel? What relationships exist between these subsystems?*
b) ***Design of a modelling approach independent coupling mechanism:*** *How should the interactions between the continuous and the discrete subsystems (the relationships between business subsystems) with respect to the different time scales be realized?*
c) ***Design of a modelling approach specific coupling mechanism:*** *Which elements of the different submodels (SD and DEVS) should be coupled with each other and how should this be accomplished?*
d) ***Examination of advantages and limitations of our approach:*** *Does the application of our hybrid simulation approach to the analysis of business systems overcome the problems p_1 to p_5? What are the limitations of our approach?*

This design science oriented paper provides answers to the research questions a) to d) from a *radical constructivist* perspective (v. Glasersfeld 2002). Additionally, the paper is verified according to the guidelines of design science by Hevner et al. 2004. To achieve our research objectives, a literature review (section 2) is carried out first. Afterwards, the technology-based artifact, our approach of a hybrid simulation system is constructed (section 3). Furthermore the applicability of the approach is exemplified by a market case study (section 4). Finally, we summarise strengths and weaknesses of our approach and give an outlook to further research (section 5).

2 LITERATURE REVIEW

The term *hybrid system* is used with different meanings. Therefore, we need to explain our understanding of a hybrid system. In this section we describe different types of systems, including different types of hybrid systems firstly. These descriptions are based on a formal mathematical notation. Afterwards, we use this classification to explain our understanding of hybrid systems and to examine research results in the field of hybrid systems with regard to our research questions. From the perspective of methodology, the literature review is carried out according to the guidelines by Cooper (1998).

In a mathematical sense, a system is a set of interacting components (v. Bertalanffy 1973). Components are either sub-systems or elements of a system. Subsystems possess the same characteristics as systems. They feature interacting components. In contrast to subsystems, elements cannot be decomposed further. Following Ferstl (1979) and Mesarovic and Takahara (1975) we distinguish between *general systems*, *input output systems*, *state space systems*, *finite state automatons* or *general dynamical systems*. Furthermore, we make a distinction between *time-continuous* and *time-discrete dynamical systems* (cf. Figure 1). While time-continuous simulation systems are a special kind of time-continuous dynamical systems, time-discrete simulation systems and agent based *simulation* systems are subtypes of time-discrete dynamical systems.

As we already mentioned, there is no consensus of the term *hybrid system* in systems science research. On the one hand, systems that consist of subsystems of different system types are called *hybrid systems* (Almeder & Preusser 2007, Godding & Sarjoughian 2003, Lee & Kim 2000, Venkateswaran

& Son 2005). An example is the coupling of a time discrete dynamical system with a control system. The control system is often called model predictive control (MPC) model (Sarjoughian et al. 2005). The MPC model is most frequently an input output system, i.e. a linear program. This research area is called computer aided control system design (CACSD) and is not in our focus of research.

On the other hand, the term *hybrid system* is used for describing systems, which feature subsystems with time-continuous behaviour and subsystems with time-discrete behaviour (Carloni et al. 2001, Cellier 1986, Rabelo et al. 2003, Schaft & Schumacher 2000, Venkateswaran & Jones 2004). Time-continuous and time-discrete event *simulation* systems are the system types that are being used most commonly (Lee & Cho & Kim 2002, Rabelo et al. 2003, Rabelo et al. 2005, Rabelo et al. 2007).

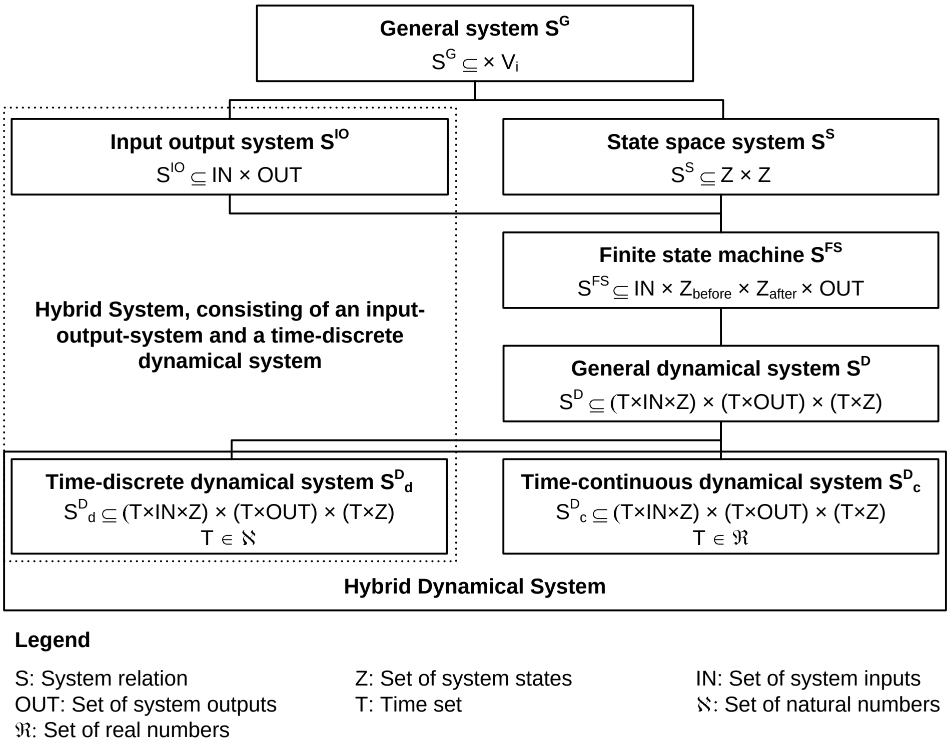

Figure 1. Types of systems.

To avoid misconceptions, we denote a *hybrid system*, a system that consists of different types of systems (e.g. an input output system and a dynamical system; cf. Figure 1). Furthermore, we refer to dynamical systems consisting of time-continuous and time-discrete dynamical subsystems as *hybrid dynamical systems*. A *hybrid simulation system* is a hybrid dynamical system with at least one time-continuous and one time-discrete simulation subsystem.

In this paper we focus on hybrid simulation systems which consist of System Dynamics simulation subsystems and Discrete Event (Simulation Sub-)Systems. Some investigations have already been carried out in this field (Lee & Cho & Kim 2002, Rabelo et al. 2003, Rabelo et al. 2005, Rabelo et al. 2007, Venkateswaran & Jones 2004). These publications present research results in the examination of the use of hybrid simulation models for modelling and analysing business systems. But these papers neither provide an answer to the research question a), which subsystems of a business system should be represented by a time-continuous or a time-discrete simulation submodel, nor do they show how to couple these submodels with respect to their different time behaviour and their different model elements (research questions b) and c)). In addition, they do not elaborate the advantages of integrated simulation analyses over separated analyses (research question d)). Some of the papers explore subsystems of business systems, such as supply chains or hierarchical production planning systems but do not consider the business system as a whole (Lee & Cho & Kim 2002, Venkateswaran & Jones

2004). All papers do not define the coupling mechanisms between subsystems with different time behaviour in detail.

3 DESIGN OF A HYBRID SIMULATION APPROACH

3.1 Modelling of Business Systems Respecting Time-Behaviour

The first part of the approach presented here is a structural model of business systems, which we denote as *model layer hierarchy* (cf. Figure 2). It defines submodels of a business system model and their relationships. It provides an answer to our research question a).

The business system model is decomposed using the phase principle of tasks (Ferstl 1992) into a *model of a managing system* and a *model of a servicing system*. The managing system model is further decomposed into three submodels, with each of them representing one model layer. The decomposition is accomplished with respect to different time behaviours that are suitable for modelling these particular parts of a business system.

The first layer of the managing system model represents the *strategic management* of a business system. Its task is to take care of the long-term success of a business system, which means, that it has to maintain stability of the business system. For this purpose, relevant tasks are the formulation of strategies, their selection, implementation and monitoring (Mintzberg et al. 2003). As an example, one task of the strategic production planning is to determine the product/market combinations of a business system and the sales targets based on market research. Simulation models of this layer feature a *time-continuous behaviour*. While analyses of this layer constitute macro analyses, analyses of the other layers constitute micro analyses.

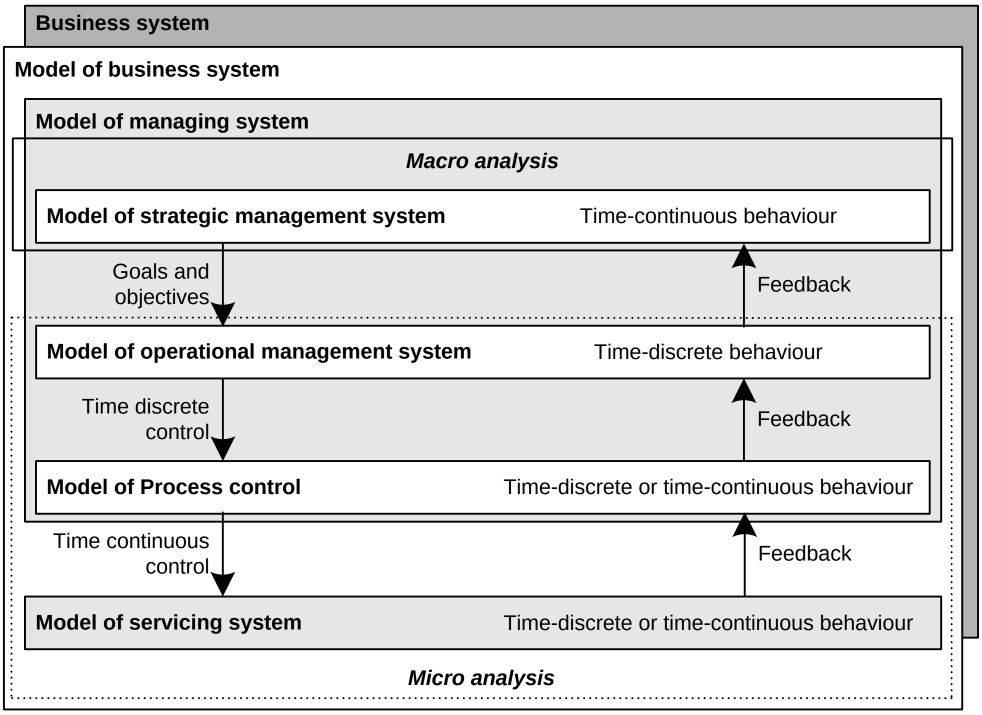

Figure 2. Business systems model layer hierarchy.

Models of macro analyses interact with models representing the *operational management* by using continuous, although mostly periodic reports and permanent goal settings. From the *perspective of systems theory*, both layers form a feedback loop (Ferstl 1979). The task of the operational management is the planning, controlling and monitoring of the implementation of strategies. The time horizon of this layer is short. State changes occur more frequently than at the strategic management layer. At the operational management layer, for example, the sales targets for goods and services are determined on a daily or weekly basis with respect to the constraints set by the strategic production planning. Consequently, the production is controlled and monitored. In contrast to models of the strategic management layer, simulation models at this layer feature *a time-discrete behaviour*. They interact with models of the *process control layer* in a time-discrete manner using control messages.

The process control layer contains models of control systems for resources of the servicing layer (i. e. numeric control (NC-) systems). The *servicing layer* represents the production processes of a business system. Depending on the analysed business systems and the perspective, models representing this layer as well as process control models could feature either *time-discrete*, *time-continuous* or *hybrid behaviour*. Car manufacturers, for example, feature a servicing system that could be described by using a time-discrete simulation model. In contrast, chemical processes in a chemical plant are mainly described by a time-continuous simulation model. However, in this paper we concentrate on integrated macro and micro analyses with time-continuous macro and time-discrete micro models.

3.2 Coupling of Time-Discrete and Time-Continuous Dynamical Systems

To realise the interactions between time-discrete and time-continuous subsystems of hybrid simulation systems and to answer our research question b), we introduce a coupling mechanism for hybrid dynamical systems extending Nixdorf (2003) and Zeiger and Praehofer and Kim (2005). The coupling mechanism abstracts from concrete simulation modelling approaches, such as SD or DEVS. The applicability of the mechanism is not limited to hybrid simulation systems. It is an appropriate mechanism for the coupling of all kinds of hybrid dynamical systems. Therefore, we denote it as a *modelling approach independent coupling mechanism*.

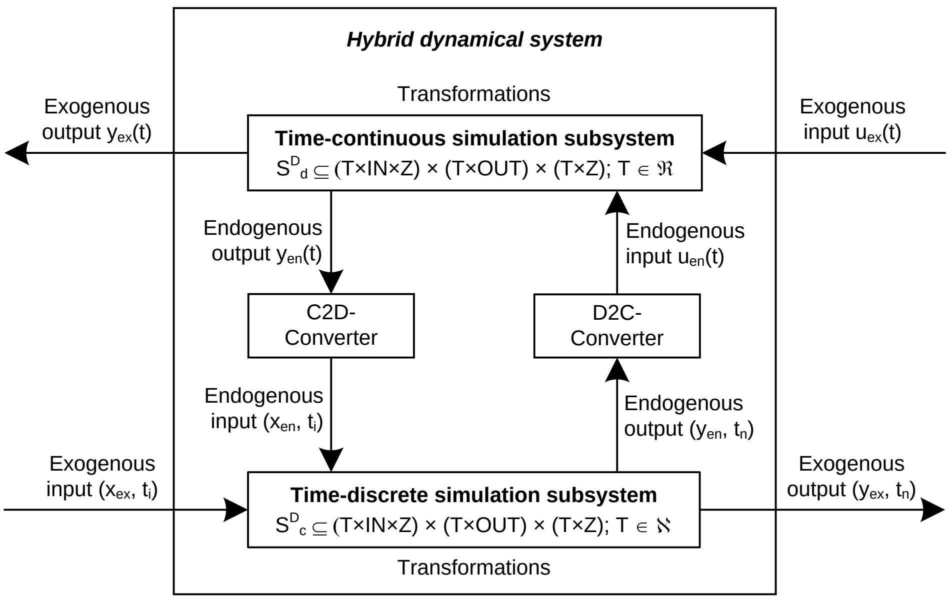

Figure 3. Abstract structure of a hybrid dynamical system.

In order to couple time-continuous and time-discrete subsystems, we need to solve the following problems:

- *Proxy relationships*: To which element of the subsystem B is an element of the subsystem A mapped to, or in other words, which are the proxies of the elements of the subsystem B in A?
- *Time axes*: State transitions take place in time-continuous, respectively time-discrete, subsystems in different times. How can a synchronisation of both time axes be realised?

To solve these problems, we introduce system components, which couple the corresponding elements of the subsystems (proxies of the subsystems) and allow a synchronisation of the time axes (answer to research question b)). Figure 3 shows the coupling of both subsystems from an outside view.

- *C2D-Converter*[1]: The task of this converter is to transform a value-continuous state variable $y_{en}(t)$ into a value-discrete variable used as endogenous input (x_{en}, t_m) of the time-discrete subsystem. The transformation will occur when the value of a state variable exceeds or undercuts a certain threshold. This generates an event triggering a state transition in the time-discrete subsystem and a change of values of the affected proxies.
- *D2C-Converter*: The task of this converter is to transform a value-discrete state variable (y_{en}, t_n) with $t_n \geq t_i$, into a value-continuous variable used as endogenous input ($u_{en}(t)$) of the time-continuous subsystem. The propagation of a state transition to the time-continuous submodel follows their occurrence in the time-discrete subsystem (jump). Afterwards, the integration of differential equations is continued.

3.3 Hybrid Simulation Using System Dynamics and Discrete Event Systems

The modelling approach independent coupling mechanism does not consider modelling requirements that are derived from the domain represented with these models (business systems).

- State changes, which occur at the operational management layer, are more frequent than state changes at the strategic management layer.
- The modelling approach independent coupling mechanism does not consider the coupling of the modelling components of the SD and DEVS simulation modelling approaches.

In order to answer our research question c), we solve these coupling problems in the following by designing a *modelling approach specific coupling mechanism*.

Different granularity of time axes: An aggregated analysis of the long-run values of state variables is carried out at equidistant time steps in the time-continuous SD models (corresponding to a macro view). Time-discrete DEVS simulation models are used for analysing single state changes, which occur in short distances of time (corresponding to a micro view). In order to couple both submodels we have to consider the time lags between state transitions in both models. State transitions in the time-continuous submodel precede, if applicable, multiple changes of the same state variable in the time-discrete submodel (proxy). Between state variables of the time-discrete submodel and state variables of the time-continuous submodel may exist an aggregation relationship that requires an aggregation of values of these variables.

Coupling of the model components of the submodels: In order to specify the coupling of model components we switch to the inside view of the submodels (cf. Figure 4). Model components of the time-continuous SD model are material or information flows, stocks or auxiliaries. Model components of the time-discrete DEVS simulation model are stationary objects, resources and entities[2]. Stocks in the time-continuous submodel serve as a proxy to stationary objects in the time-discrete submodel. State variables of the stationary objects are mapped to variables of one or more stocks and vice versa. The entering of an entity into a stationary object or the leaving of an entity out of a stationary object leads to a state transition in the time-discrete submodel. If there is at least one proxy in the time-continuous submodel associated with this stationary object, every state transition will be propagated to the time-continuous submodel. In addition, every change in the amount of a stock will be propagated to the time-discrete submodel if the amount exceeds or undercuts a certain threshold and if a proxy in the time-discrete submodel exists. This may happen in a *direct* or *indirect way*:

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[1] From an engineering perspective, the C2D-converter is often designated as a quantifier, the D2C-converter as an injector [22].

[2] For a closer look at time-discrete and time-continuous simulation systems and the differences between these systems see for example Barton and Lee (2002), Forrester (1969), Lee and Zheng (2005), Pidd (2004), Schriber and Brunner (2007) or Sterman (2000).

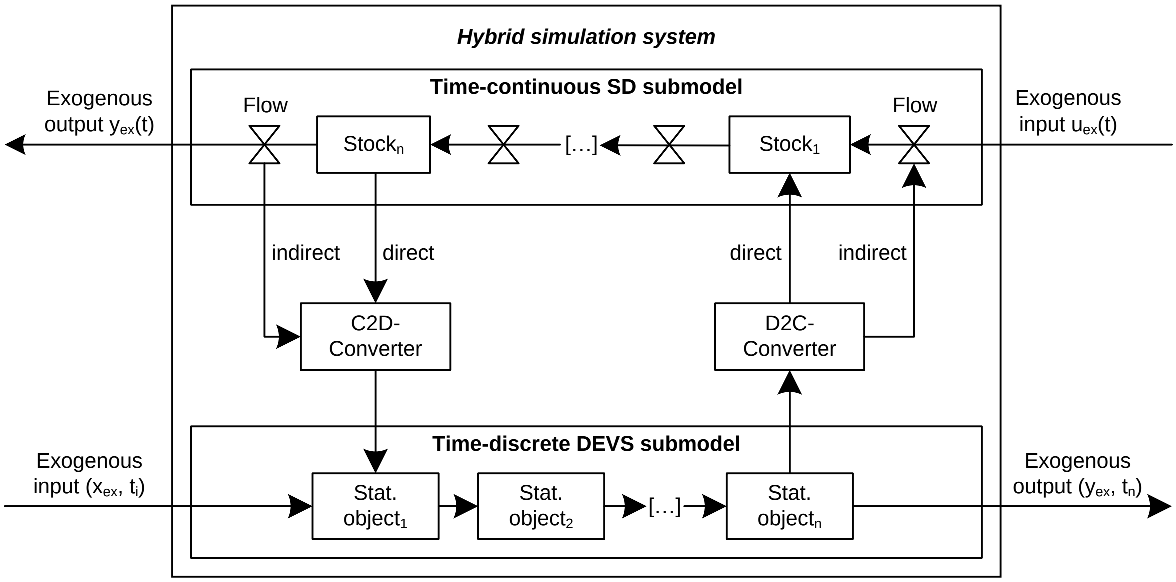

Figure 4. Abstract structure of a hybrid simulation model using SD and DEVS

- *Direct coupling*: An entity entering or leaving a stationary object directly leads to a change of the stock amount. The value-discrete presented state variable is transformed by the D2C-converter to a value-continuous variable and the stock amount is adjusted. The stationary object can be functionally interpreted as a rate increasing or decreasing the stock amount. The stock amount influences state variables or distribution functions of one or more stationary objects, and vice versa. In this case, the value-continuous stock amount will be transformed by the C2D-converter to a value-discrete variable. An event to initiate the state transition will be generated.
- *Indirect coupling*: An entity entering or leaving a stationary object leads to a change of the stock amount indirectly by changing one or more rates. As stated above, the value-discrete state variable will be transformed by the D2C-converter to a value-continuous variable. In contrast to the direct coupling, the stock amount will be changed by a rate indirectly. The time-discrete submodel can be functionally interpreted as an auxiliary parameterising the rate. The value of the rate influences state variables or distribution functions of one or more stationary objects and vice versa. Analogous to the direct influence, the value-continuous and time period oriented rate will be transformed by the C2D-converter to a value-discrete time space oriented variable and an event will be generated.

4 APPLICATION OF HYBRID SIMULATION TO A MARKET CASE STUDY

In this section we present an example for conducting an integrated macro and micro analysis using a hybrid simulation model of a business system which consists of a time-discrete DEVS simulation submodel (micro model) and a time-continuous SD simulation submodel (macro model) (cf. Figure 5). Although being fictitious, it has been constructed following developments in the global economy over the last years. According to our model layer hierarchy, the model represents the strategic and operational management system layers and the servicing system layer of a business system. It also covers the relationships between these three layers.[3] The coupling of the time-continuous and the time-discrete submodels is realised by using direct coupling (cf. section 3.3).

[3] Due to complexity reasons, the process control layer as well as the feedback relationships between the layers of the business system are omitted.

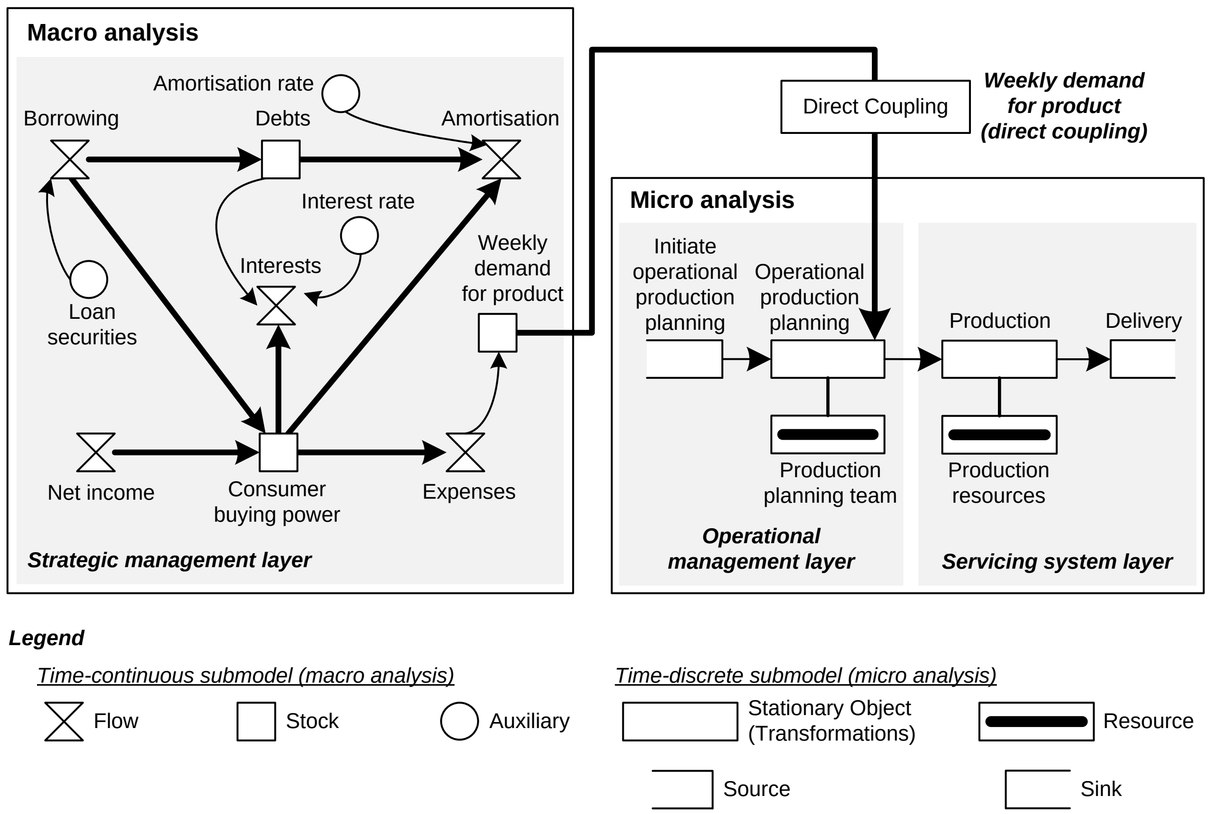

Figure 5. Structure of the simulation model

The investigation objective is to determine the servicing system (production resources) capacity utilisation. Therefore, the time-discrete micro model encompasses parts of an operational management and of a servicing system. The exogenous output of the micro model is just *one product*, which is manufactured by using the concept of mass production. The task of the operational management system is to determine the *daily product output* on the basis of the customer demand (endogenous input of the micro model and endogenous output of the macro model). After that, *production orders* are generated and passed to the servicing system. Entities in this model are *production orders* and *products*. The model contains stationary objects, which carry out the tasks *operational production planning* and *production* as well as stationary objects, which represent *resources (actors).*

The macro model represents the strategic management layer. It contains stocks, flows and auxiliaries as well as the relationships between these items. The model output is the weekly demand for the product which is produced in the servicing system layer. This demand is calculated by using the consumer buying power. The buying power is increased by the net income of a consumer and the money that is borrowed (i.e. by using credit cards). It is decreased by the interests on credit and the amortisation of loans. Interests and amortisation are influenced by the *debts* of the consumer, the *amortisation rate* and the *interest rate*. The debts are collateralised by *loan securities*. The debts are directly proportional to the loan securities: the higher the loan securities, the more money the consumer is able to borrow. However, they also have to spend more money on interests and amortisation. We assume that every consumer spends a certain amount of his expenses on the product we produce in our servicing system. The demand results from the expenses, the number of customers, the price of the product and the assumed market share, which the investigated business system holds.

The macro and the micro submodel are coupled *directly*. The weekly demand for product, calculated in the macro model, directly influences the task of operational production planning. Here, the weekly demand is used for calculating the daily production output. This value is used to generate the production orders as mentioned above. Simulation experiments conducted with this model show the relationships between the levels of loan securities, the consumer's buying power and the consumer's expenses as well as the relationship between the consumer's expenses and the capacity utilisation of the production resources. If the value of the loan securities decreases, the consumer buying power and the consumer's expenses will decrease significantly (cf. Figure 6). Therefore, the product demand decreases as well as the production system's capacity utilisation. When the values of loan securities increase, other values of other variables will increase as well. Figure 6 shows the development of the consumer's expenses which feature the SD-pattern *s-shaped growth with overshoot and collapse* (Sterman 2000) as well as the utilization of the production resources over time (the scale of the y-axis has been normalised).

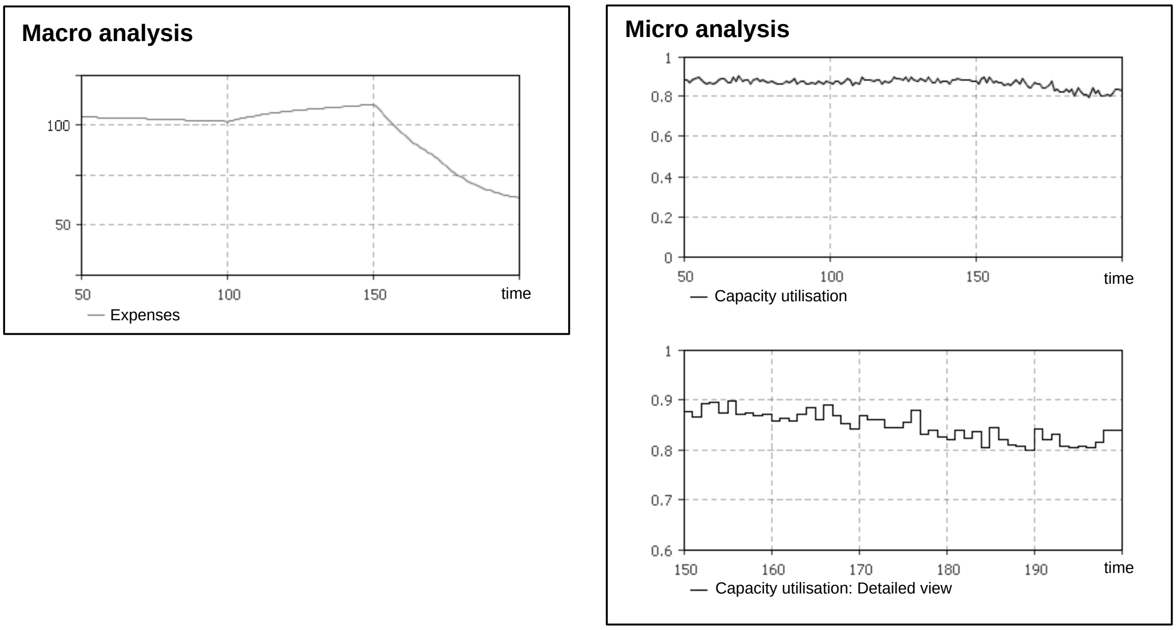

Figure 6. Findings of the integrated analysis

A simulation using the hybrid model (e.g. an integrated micro and macro analysis) offers advantages compared to isolated simulations of the time-continuous and the time-discrete model. The consistency of the time behaviour of the customer demand is ensured in both models as the findings of the macro analysis are applied directly and automatically to the micro model (solution to p_1). Components representing the time behaviour are implemented only once (solution to p_5). Therefore, no redundancy of model components is needed (solution to p_2). It is not necessary to decompose the investigation objective into a sub objective to determine the time behaviour of the consumer's expenses (and, therefore, the weekly product demand) and a sub objective to determine the resource utilization of the production system afterwards (solution to p_4). The macro and the micro analysis are made by using one hybrid simulation model. As a result, the effort of model construction and of conducting simulation experiments is lower, as tasks do not have to be carried out twice (solution to p_5).

5 CONCLUSIONS AND FURTHER RESEARCH

In this paper we introduced a new approach to analyse complex business systems. This artefact, our research contribution consists of a *structural model of business systems* and a *modelling approach for integrating DEVS and SD submodels by two coupling mechanisms*. Furthermore, we presented an example of an integrated macro and micro analysis, conducted with a hybrid simulation model. At this point, the research questions a), b) and c) have already been answered.

The problems of isolated analyses, which have been introduced in section 1, have been solved as follows. The solutions to these problems represent the advantages of integrated macro and micro analyses of business systems as well and therefore, answer research question d):

- *Model consistency (p_1)*: An overlapping of micro and macro models occurs at defined interfaces. The approach ensures the behavioural compatibility of the two submodels by specific coupling mechanisms.
- *Redundancy of model components (p_2)*: The redundant representation of model components of both submodels is limited to the modelling of the proxy relationships.
- *Connection of model components (p_3)*: The connection of model components is realised by defined interfaces. Although, micro and macro views feature different time axes. In the micro view, single events with time distances measured in seconds, minutes or hours are observed. In the macro view, time dimensions such as weeks, months or years are used. This distinction requires an aggregation and disaggregation of values of model variables (cf. section 1).
- *Decomposition of investigation objectives (p_4)*: As a result of conducting integrated macro and micro analyses, a conventional decomposition of investigation objectives is not necessary.
- *Modelling and model investigation effort (p_5)*: The costs of constructing and analysing an integrated simulation model are less than the costs of constructing and analysing two models. Redundant task executions are omitted and the use of well-known simulation modelling approaches reduces the preproduction costs.

Nevertheless, the approach has some *limitations*. Existing simulation tools do not feature different time axes for the time-continuous and time-discrete submodels. The simulation tool ANYLOGIC[4], for example, offers only one time axis for both submodels. For other hybrid simulation tools, refer to Carloni et al. (2001). Points in time of events in the time-discrete submodel and points in time of the time-continuous submodel (integration time step) have to be mapped to this one time axis. Furthermore, the approach lacks sufficient support for the identification of proxies in submodels with different time behaviour. Further research is needed to provide the modeller with an adequate method. Despite these difficulties, the approach has the potentials of tackling economic problems by using an integrated micro and macro view. In the future we will investigate the completeness of the introduced coupling relationships between model components of the submodels and develop a method for identifying proxies in submodels of a hybrid simulation model. In addition, we will evaluate the applicability of the approach to practice in an extensive real world case study.

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