Simulation Based Parameter and Structure Optimisation of Discrete Event Systems

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Abstract

Modelling and simulation based on discrete event systems is used routinely in research and industrial applications e.g. in the design, planning and real time control of manufacturing systems. An advanced, but now well established, technique is modelling and simulation with integrated parameter optimisation to improve system performance. In using these established approaches model structure is considered to be fixed as the relationships between model elements are defined during model development. As model performance is optimised it may be necessary to redesign the model structure, normally carried out manually by an analyst using previous simulation results, observations or decisions based on previous experience.

With increasingly complex, flexible and reconfigurable discrete event systems such as manufacturing systems, modelling and simulation methods are becoming more challenging. As the number of possible structure variants increases the potential benefit of automatic model structure optimisation becomes significant. The research reported in this thesis details a new approach providing automatic reconfiguration and optimisation of both model structure and model parameters. This is achieved through a combination of simulation, optimisation and model management methods. Simulation is used to determine current model performance and an optimisation method, assisted by model management, searches for an optimal solution with repeated model parameter and model structure changes. In contrast to conventional modelling and simulation methods this approach employs a meta-modelling method. It defines a set of model structure variants and includes a model base with pre-defined basic components. With this meta-modelling method the model management can determine specific model structures and create executable models.

To validate the simulation based optimisation approach a prototype was implemented. Several variants of a Photofinishing Laboratory part were modelled. In different experiments the introduced approach and the prototype were validated.

This research project extends the work of Pawletta et al. [35]...[46], supports other projects of the Research Group Computational Engineering and Automation at Hochschule Wismar University of Applied Sciences Technology, Business and Design, Germany and follows another collaborative LJMU School of Engineering / Wismar research project in this field [23] [24].

Acknowledgements

It seems impossible to reach the end of this long process without the support from many others, who have helped me so much along the way.

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Chapter 1

Introduction

1.1 Preamble

Often it is of interest to study a system to understand the relations between its components or to predict how a system is responsive to changes. Sometimes it is possible to directly experiment with the system. However, this is not always possible e.g. due to costs when a manufacturing system has to be stopped, changed or extended. Often the system even does not yet exit. A model, defined as a representation of the system in order to investigate it, can solve this dilemma. Generally, it is sufficiently to abstract the system with a view to the analysing the issues under investigation. In terms of modelling and simulation this abstract is named the simulation model.

A system can be classified into discrete or continuous: “Few systems in practice are wholly discrete or continuous; but since one type of change predominates for most systems, it will usually be possible to classify a system as being either discrete or continuous.” [25]. The analysing issue also plays a decisive role. An analogue printer in a photofinishing lab is a typical example. It is possible to analyse the machine at a very low level with the continuous movements of machine components and analogue film material when the objective is to optimise the component interaction. Another, discrete viewpoint could be the number of pictures and the length of photographic paper handled in a specific amount of time when the objective is to plan throughput and the necessary staff.

Simulation models as a particular type of mathematical system models can be classified too, e.g. as being static or dynamic, deterministic or stochastic, and discrete or continuous. A static simulation model represents a system at a particular time whereas a dynamic simulation model represents system changes over time. A deterministic simulation model does not contain any random variables whereas a stochastic simulation model has in minimum one random variable as an input. Discrete and continuous models can be discrete and continuous systems as described above. One specific type of discrete systems is the discrete event system (DES) where state variables change at discrete points in time during simulation.

One of the most important applications of modelling and simulation based on discrete event systems are manufacturing systems. These systems have been modelled since the origins of manufacturing. From the civilisations of the ancient world to the first industries through to current high-technology production, managers and engineers have thought about the complexities of manufacturing systems [27]. As computers developed they became an increasing important means of modelling and simulation. The expanding capability of computing systems and the increasing demands of engineers and managers planning, implementing and maintaining manufacturing systems have been pushing the boundaries of modelling and simulation research. With the decreasing costs of computing systems, modelling and simulation applications have become an integral part of industrial practice.

Simulation has been used widely and successfully to support the design of new production facilities and material handling systems and to evaluate variants of existing systems. Applications for production, warehouse-management and material handling control can incorporate simulation techniques to evaluate staffing and operating rules, changes of material handling and system layout or the effect of capital investment. An important advantage in using modelling and simulation techniques is the possibility of evaluating changes before making investment decisions and without disturbing the existing system.

Recently, with increasing globalisation, the competition conditions for manufacturing have been changing fundamentally. A key shift is the need to move from increasing product quantity to a combination of increasing quantity and a drive for manufacturing flexibility. As the number and the speed of product innovations increase, the time to market and the marketing life of a product decreases. As a consequence manufacturers have to extend the general objective "cost saving" to "time and cost saving" [29]. To support this market trend manufacturing systems will increase in complexity with increasing automation, flexibility and degree of computerisation. This also implies increased requirements for production planning. For many companies modelling and simulation together with a combined optimisation is a strategy to fulfil these requirements. Because of the increasing production planning requirements modelling and simulation environments have to meet these increasing needs.

1.2 Rational for Simulation based Optimisation

Successful systems have been stable over a long time, solved real problems and demonstrated return-on-investment (ROI). New, identical copies of such systems are not risky because they are proved. However, it is not possible to guarantee that innovative system changes will ever generate their ROI. Simulation enables system analysis with time and space compression, provides a robust validation mechanism under realistic conditions and can reduce the risk of implementing new systems. Validation is achieved using a series of qualitative and quantitative experiments with changes of system variables and structures. Pilot projects using real systems with reduced size and/or implemented in a low-risk laboratory environment, can provide analysis results. Such real experiments take time and cost. Hence, a large number of alternatives imply an initial pre-selection. Modelling and simulation can lower the number of alternatives analysed in real experiments as the final step [8].

One reason for system changes is the search for a better overall performance. Under the focus of simulation this means the search for a set of model specifications e.g. input parameters and/or structural assumptions, that leads to an optimal model performance. For all possible variants the range of parameter values and the number of parameter combinations may be too large to implement and simulate manually. A method to automate this is needed. The example described in chapter 6 demonstrates this problem. Even though only a fraction of the complete manufacturing system is modelled the number of possible variants is overwhelming.

Many real word systems are too complex to be expressed by mathematical models. But mathematical models are a precondition of optimisation methods. This leads to a contradiction [2]:

- Pure optimisation models are not able to handle the complexity of both system behaviour and structure.
- Pure simulation cannot find an optimal solution.

⇒ Simulation based optimisation resolves this contradiction through a combination of both methods.

Research and application of simulation based optimisation has seen a significant development in recent years. A Google search on 'Simulation Optimisation' in 2006 found ca. 4.000 entries [2] in comparison to a search in 2008 with almost 80.000 entries among others articles, conference presentations, books and software.

Until a relative short time ago, the simulation community was resistant to the use of optimisation tools. Optimisation models seem to over-simplify the real problem and it was not always clear why a certain solution was the best [8]. The situation changed at the end of the 90s. An ACM Digital Library [57] search on 'Simulation Optimization' found 16.000 articles between 1960 and 2008. A significant number (15.500) of articles has been published during the last 20 years and only 500 articles in the 28 years before. Two reasons

for this change may be the advances in modelling and simulation methods and increase of computing power over the last two decades that has enabled simulation based optimisation.

Currently there are several algorithms to change simulation model parameters to establish solutions with good performance and methods to compare different solutions in terms of quality. Many commercially available discrete event or Monte Carlo simulation software packages contain optimisation methods to search for optimal input and system parameter values [3] e.g. WITNESS with the optional optimisation packages WITNESS Optimizer, ARENA with the additional package OptQuest for Arena [7], SIMPROCESS and SIMUL8 with OptQuest optimisation technology [8].

1.2.1 A Context for Simulation in Manufacturing Systems

The application of manufacturing simulation focuses on modelling the behaviour and the structure of manufacturing organisations, processes and systems. Simulation in a manufacturing system can be used at different phases of manufacturing system lifetime and at different system levels as depicted in figure 1.1. Traditionally, simulation has been used in the planning and design phase dating back to the beginning of the 1960's [26]. Today simulation models are used in all phases of life cycle and at all system levels (see figure 1.1) [19]. Recent developments indicate approaches that also use simulation as an integral part of real time machine control [23] [24] [28].

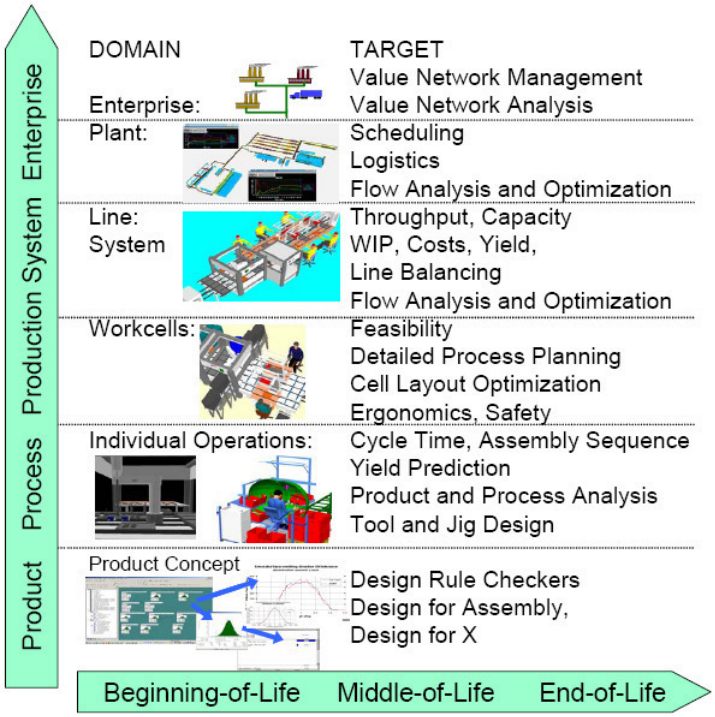


Figure 1.1 Modelling and simulation of Manufacturing Systems (source [19])

A broad variety of simulation tools are available for manufacturing systems. Historically they can be classified into two major types: simulation languages and application-oriented simulators [26]. Simulation languages are very general. Models are created by coding their behaviour and structure and are similar to a general computer language. Simulation languages provide very high flexibility in model creation but are complex in use for non-scientists and non-engineers. Application-oriented simulators specialise in a given application class. Models are often developed with a graphical user interface based on components, dialog boxes, context menus etc. This eases model development for non-technical users but could lead to reduced flexibility for specific problems [26]. Recent developments indicate that both types are adapting typical characteristics of the other e.g. a simulation language can use a graphical modelling user interface to internally produce code which can be manually altered later.

In summary it is possible to differentiate between general purpose and application-oriented simulation packages. The first are general packages but may have special features for certain application. Examples of general-purpose simulation packages are Arena,

AweSim, Extend, GPSS/H, Micro Saint, MODSIM III, SIMPLE++, SIMUL8, SLX and Taylor Enterprise Dynamics Developer. Examples of application-oriented simulation packages for manufacturing are Arena Packaging Edition, AutoMod, AutoSched, Extend + MFG, ProModel, QUEST, Taylor Enterprise Dynamics Logistics Suite and WITNESS. Short overviews about the above packages and their main feature can be found e.g. in [7] [25] [26].

Other classifications of simulation packages exist, e.g. the differentiation between continuous and discrete simulation. Few systems are completely discrete or continuous but in many systems one is dominant or analysis objectives require the use of a specific simulation type. Due to the stochastic nature of systems continuous processes can be approximated by stochastic distributions with start and stop events. Hence, a continuous system or sub system can be described by a discrete event system. For example, in an automobile assembly line simulation discrete events dominate but of course it would be possible to continuously describe sub systems e.g. work piece movements. In contrast in a chemical plant continuous state changes prevail but the switch of a valve could be modelled discretely.

In this research a general, theoretical established, discrete modelling and simulation approach is used. Hence the research results are general statements and applicable to generic simulation approaches and application specific systems respectively. The Discrete Event System Specification (DEVS), used in this research, is a formalism based on discrete event models. It supports a modular, hierarchical model construction and claimed to be a general and powerful approach in the field of discrete event simulation. The formalism can describe models with a formal specification and simulation model execution with generic simulation algorithms.

1.2.2 Aims and Objectives

The research addresses a fundamental problem of simulation based optimisation. The technique is well established but is restricted to the optimisation of system parameters. In

using these established techniques model structure is considered to be fixed as the structure of model elements is defined during model development before an optimisation experiment. As model performance is optimised it may be necessary to redesign the model structure. This would conventionally be done manually by an analyst using previous simulation results, observations or decisions based on previous experience. This manual process cannot guarantee the global optimal solution. The aim of this research is to develop an approach to discard the manual changes i.e. to develop a combined, simulation based parameter and structure optimisation.

The objectives are:

- Carry out a literature analysis on simulation based optimisation and search methods
- Carry out a literature analysis on the specification and simulation of modular, hierarchical discrete events systems, particularly the Discrete Event System Specification (DEVS) and DEVS extensions
- Advance the established approach of a simulation based parameter optimisation to a simulation based parameter and structure optimisation
- Develop a modelling and simulation method based on DEVS and DEVS extensions to create a merging formalism which combines advantages of different approaches
- Investigate model management and model generation methods
- Investigate appropriate optimisation and search algorithms
- Validate the research and developed approach using an industrial application
- Publish the results in peer reviewed journals, at conferences or in other research publications

1.2.3 Cost Reduction with the Aid of Simulation based Optimisation

The results of this research enable two different possibilities for cost reduction:

1. With increasingly complex, flexible and reconfigurable manufacturing systems the number of possible structure variants increases. In using established approaches it

may be necessary to redesign the model structure between two parameter optimisation runs, normally carried out manually by an analyst using previous simulation results, observations or decisions based on previous experience. This is time consuming and potentially error prone. With this new approach providing automatic reconfiguration and optimisation of both model structure and model parameters the process becomes shorter and the ability to find an optimal solution increases.

2. Many manufacturing systems have the potential to be optimised. Using existing machines, facilities and processes, optimisation could be used to find a new layout and system dimension with improved performance.

The application of this research described in the thesis demonstrates both aspects.

1.3 Methodology and Structure of the Research

The four main areas investigated in this research are:

1. Introduction of *simulation based optimisation* approaches with regard to an extension to a structure optimisation method
2. *Modelling and simulation* method based on the Discrete Event System Specification (DEVS)
3. *Model management and model generation method* using the System Entity Structure/Model Base (SES/MB) framework
4. *Employing* the approach with a real life manufacturing problem

A new approach was established based on the methods 1, 2 and 3. Through the linking of the methods and the definition of appropriate interfaces between them they constitute a new approach to a combined and automatic simulation based parameter and structure optimisation. Figure 1.2 depicts the connections between the investigated areas.

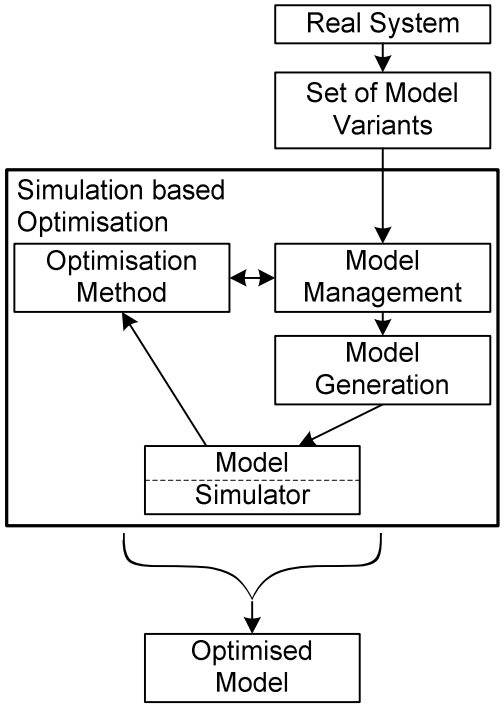


Figure 1.2 Research area structure

1.3.1 Simulation based Optimisation

Modelling and simulation with integrated parameter optimisation to improve model performance is an established technique. In using these established approaches model structure is considered to be fixed as the relationships between model elements (machines, facilities, conveyors etc.) are defined during model development before the optimisation experiment. As model performance is optimised it may be necessary to redesign the model structure after the optimisation experiment. This is normally carried out manually and repeatedly by an analyst with subsequent optimisation experiments.

In established parameter optimisation methods the number of parameters and their domains specify the search space. Depending on the optimisation method the search space is traversed i.e. the optimisation method needs a specific knowledge about the search space bounds. Certain points of the search space are analysed. Each point defines a certain parameter value set. The model is initialised with this parameter value set and subsequently simulated.

The extension using a structure changing facility means broadening the technique to a parameter and structure optimisation. Additional variables with their associated domains are describing possible model structure variants. The combination with the set of parameters defines the new search space of the extended optimisation problem. Methods to transform the set of parameters and structures to a search space definition and vice versa a search space point to a model structure and model parameter values are an integral part of the broadened technique.

1.3.2 Modelling and Simulation

Many different concepts and methods of modelling and simulation exist. This research is restricted to the discrete event system specification formalism, characterised by continuous time and discrete state changes and modular, hierarchical modelling and simulation. The investigated und further developed discrete event system approach is based on DEVS introduced by Zeigler [66] [67] [68]. This approach is one of the most developed, theoretical well-founded discrete event approaches. DEVS supports the definition of modular, hierarchical systems and incorporates well-defined simulator algorithms.

A crucial part of the research is the analysis of the discrete event system specification and the existing extensions with regard to simulation based parameter and structure optimisation and its application in a prototype implementation. Based on the Classic DEVS formalism [66] a broad range of publications with several extending approaches are available. For the application of this research within the manufacturing systems domain certain Classic DEVS extensions were incorporated to establish the Extended Dynamic Structure Discrete Event System specification formalism (EDSDEVS). Consequently a formal concept for this unified specification was developed. The formalism was verified with examples from [66], a benchmark application [18] and industrial applications [16] [17].

This research is a key element of a major search project of the Research Group of Computational Engineering (RG CEA), Hochschule Wismar University of Applied Sciences Technology, Business and Design[1].

1.3.3 Model Management and Model Generation

In a further crucial area of the research the following key features of a model management as part of a simulation based structure optimisation were developed:

- Declarative specification of different model structures
- Definition of a method for external controlled model structure selection
- Definition of an interface between model selection and model generation

To specify a set of modular, hierarchical models an approach has to be able to describe three relationships: (i) *decomposition*, (ii) *taxonomy* and (iii) *coupling* [52] [66] [69].

(i) *Decomposition* means the approach has to be able to decompose a system called entity into sub-entities.

(ii) *Taxonomy* means the ability to represent several, possible variants of an entity called specialisations.

(iii) To compose an entity from sub-entities these have to be connected. This is the meaning of a *coupling* relationship.

The System Entity Structure/Model Base (SES/MB) approach is able to describe these three relationships [52], [66], [69]. The original SES/MB approach was developed to assist a manual model design process for modular, hierarchical models using a tree like definition with different node and edge types and a model base containing basic components. An essential demand for an appropriate model management method is the external controllability. The SES/MB approach has to be changed to comply with this demand.

Based on the adapted SES/MB approach three interfaces around the model management method were designed. The first interface is a model set definition based on a

[1] Research Group Computational Engineering and Automation, http://www.mb.hs-wismar.de/cea/

XML file structure. This interface is deployed to create a specific SES/MB structure. In future extensions the development of a graphical SES/MB modeller based on this interface would be possible. The second interface delivers model generation information to a model generator. It is based on a XML file structure definition. This interface represents the connector to the modelling and simulation method. The third interface communicates with the optimisation methods during the initialisation and the optimisation phases:

1. In the initialisation phase it delivers information about the search space defined by the set of all possible model structure and model parameter variants to the optimisation method.
2. During the optimisation phase it receives information from the optimisation method about the currently investigated search space point. This information is used to select the corresponding model structure and initialises the model parameters. A subsequent model structure validation is a crucial part of the model structure selection.

1.3.4 Implementation and Employment

In this research methods and algorithms were implemented using the MATLAB Scientific Computing Environment [58].

1. The modelling and simulation toolbox was not started from scratch. A pre-release of the modeller and simulator published in [41] was the starting point. These sources were adapted to the current MATLAB version with a new object-oriented programming principle and were extended step-by-step. Each extension was validated with test models for example those introduced in [66]. Each important stage of the research was published and subject to peer review [16] [17] [18] [34].

   A simulation model was implemented as a basis for later optimisation. This model uses results, observations, structures, parameter etc. gathered by the author of this thesis during several projects which were realised by the supporting company

Syntax Software[2]. The company is a leading production and machine control software developer for the photofinishing industry. The final model was validated with original production data taken from photofinishing applications implemented by the author.

2. The model management toolbox was developed and tested using conventional software engineering techniques.
3. The optimisation method used the commercial available Genetic Algorithm Toolbox [59].
4. The research application is based on industrial experience of the author. The germ of the idea to optimise structure comes from a project enquiry made by the Kodak Photofinishing Department to Syntax Software 6 years ago. The project was not realised because Kodak closed their European photofinishing business.

To validate the new approach all possible model variants were simulated. The simulation results are compared with the result of the automatic structure and parameter optimisation. This procedure and its results are described and discussed in chapter 6.

1.4 Research Outcomes

The outcomes of this research can be divided into four parts:

1. Development of an approach for a combined, simulation based model parameter and model structure optimisation

   The extension of the established simulation based parameter optimisation by a controllable model management is the fundamental idea behind this research. Through this inclusion of a model management the optimisation method can simultaneously control parameter changes as well as model structure changes to find an optimal system configuration.

2. Development of an Extended Dynamic Structure DEVS Formalism

[2] SyntaX Software Inh. Jörn Satow formerly SyntaX Software O.Hagendorf J.Satow GbR, Schweinsbrücke 9, 23966 Wismar, www.syntaxsoft.de

Classic DEVS and DEVS extensions has been a research topic since more than 30 years. The extensions have one joint attribute: they are based on the Classic DEVS formalism. Hence, the decision on one DEVS extension inhibits the use of advantages of another one. In this research selected extensions are combined to create to a merging formalism to combine the advantages of different approaches.

3. Validation of the new approach

   The approach was successfully validated with a simulation based optimisation experiment using an industrial application. All variants of the application were calculated and the results compared with the optimisation experiment. The global optimal result was found with a probability of 47%. With an error of 3% of the system performance an optimal result was found with a probability of 68%. To find an optimal result, on an average 70% of the search space were analysed. With a second experiment the dependency of optimisation results on search method configuration was shown. However, the finding of an optimal search method configuration was not within the scope of this research.

4. Publication of results

   Results and intermediate steps have been published in a peer-reviewed journal and as a book chapter and have been presented at international conferences.

1.5 Contribution to Knowledge

This research has resulted in two novel formalisms:

1. an approach to extend the established simulation based parameter optimisation to a combined simulation based parameter and structure optimisation which automatically change system structure and parameter values to improve the overall system performance
2. an Extended Dynamic Structure Discrete Event System Specification (EDSDEVS) as an enhancement and combination of the Discrete Event System Specification and

some of its different extensions. The EDSDEVS formalism is used as one component of the simulation based parameter and structure optimisation approach.

The contribution and the advantages of this approach are:

- The approach establishes a structure and parameter optimised model based on the definition of a set of model variants. The previous manual steps of changing structure to find an optimal system model are now incorporated into an optimisation algorithm and thus are automated.
- Through automation the probability of finding the optimal solution grows significantly in comparison to a manual search.

The contribution and the advantages of the EDSDEVS approach are summarised as follows:

- fusion of different extensions of the Classic Discrete Event System Specification
- implementation of modelling and simulation environment for research and teaching

1.6 Contents of this Thesis

The thesis is organised into three main sections as depicted in figure 1.3. In chapter 2 the simulation based optimisation is introduced, limitations are outlined and the idea of an extension of the established technique is developed. Based on this new concept of a simulation based parameter and structure optimisation the requirements of several algorithms, methods and interfaces are brought out. Essential components of the optimisation concept are appropriate model management and modelling and simulation methods.

Chapter 3 starts with a short presentation of simulation and simulation model taxonomy. The Classic DEVS formalism with the associated formal modelling concept and simulation algorithms is introduced. Concepts of selected extensions of the DEVS formalism are subsequently shown. The last part of chapter 3 introduces the EDSDEVS formalism as it was developed in the scope of this research. The formal concept of EDSDEVS, the dynamic behaviour of its components in different situation and simulation algorithms are shown.

Chapter 4 introduces the System Entity Structure/Model Base framework as an approach to organise a set of model structure variants based on meta-modelling. In chapter 5 all aspects of this approach for a simulation based parameter and structure optimisation are described in detail.

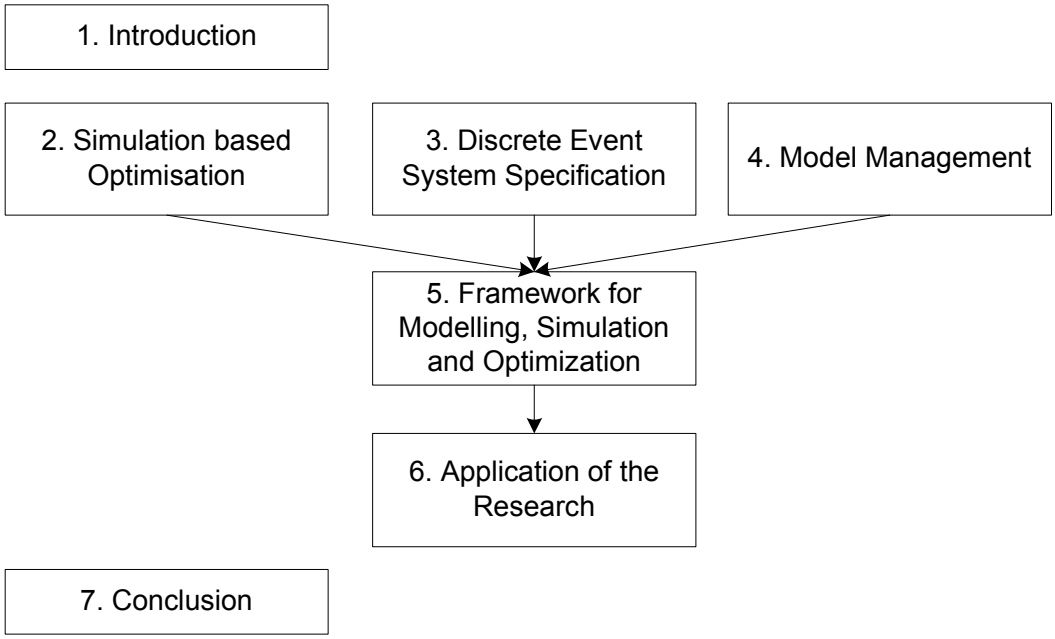


Figure 1.3 Structure of the main sections of the thesis

Chapter 6 demonstrates application of the approach with an optimisation example. The problem is taken from the industrial experience of the author. The general structure of a photofinishing lab i.e. a company for industrial production of photos and related products is described together with a daily problem and how this could be solved with the new approach of a simulation based optimisation.

The thesis concludes with a summary and suggestions for further work.

Chapter 2

Simulation based Optimisation

Optimisation is an important research topic and has the potential for significant commercial application. At the ACM Digital Library [57] the first publications on optimisation were published in the early 1950s, ca. 118.000 to date. They cover a very broad range of optimisation methods and optimisation applications. In general, the aim of an optimisation method is to find an optimal problem solution in a given search space whereas the often multidimensional search space defines the complete set of possible problem solutions.

Research and application of simulation based optimisation has seen a significant development in recent years. A Google search on 'Simulation Optimisation' in 2006 found over 4.000 entries [2] in comparison a search in 2008 found almost 80.000 entries among others articles, conference presentations, books and software.

The integration of optimisation techniques into simulation packages has been an important requirement for commercial modelling and simulation tools, shown for example in comparing two popular simulation textbooks [7] and [25] with previous editions. The third edition of Law and Kelton [25], published in 2000, lists five commercial available simulation based optimisation tools which did not exist at the time of the second edition of the book, published 1991 [15].

The following chapter introduces the ideas of combining modelling and simulation with optimisation methods. It concludes with the introduction of the new simulation based parameter and structure optimisation approach developed in this research.

2.1 Introduction

In retrospect a disadvantage of modelling and simulation is the missing optimisation capability. For many years, simulation experiments as shown in figure 2.1 have been state of the art. An analyst creates a model e.g. based on a real system, transforms the model to an executable model and executes a simulation with it. After a review of simulation results the model configuration, i.e. model parameters and/or model structures has to be manually changed by an analyst, when necessary. Using a manual procedure only a relative small number of system configurations can be examined until a suitable solution is chosen. It is not possible to guarantee the detection of an optimal or near optimal system configuration and the manual effort to find a solution can be considerable.

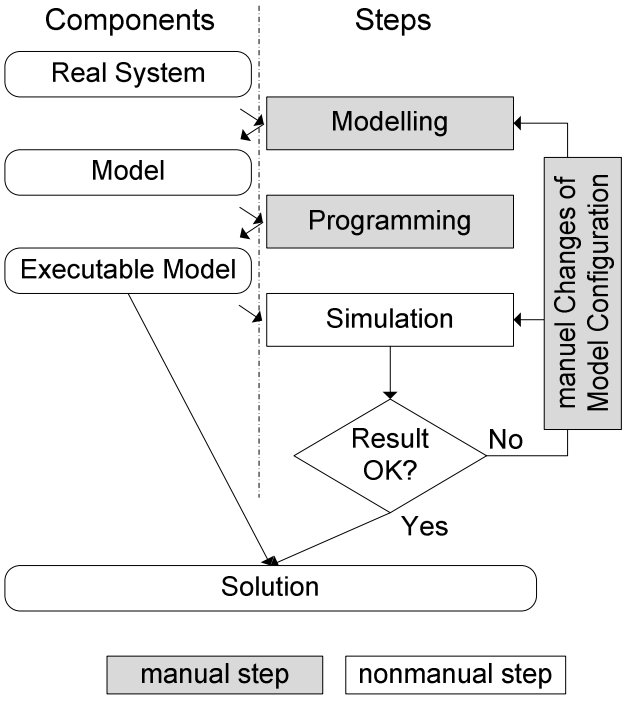


Figure 2.1 An example of an conventional simulation experiment

Through the combination of modelling and simulation with optimisation methods to a simulation based optimisation method this manual procedure can be partly automated. Mathematical optimisation generally means establishing a function minima or maxima. Simulation based optimisation means finding the best model configuration by minimising a

function of output variables estimated with a simulation method [56]. Important prerequisites are the availability of:

- suitable modelling and simulation methods

  Modelling and simulation as well as model and model parameter have to be strictly separated. With the combination of optimisation and simulation an optimisation method needs capabilities to influence the model configuration.

- suitable optimisation methods

  Figure 2.2 shows a classification of optimisation methods, identified during this research, many others and more completed classifications exists in the optimisation literature. Enumerating or calculus based optimisation methods are suitable when the search space is small enough and the problem is analytically solvable respectively. If the problem complexity is large, often search based algorithms are more appropriate. Problem descriptions with a stochastic component are another crucial reason to use a search based optimisation method. Because of the typical stochastic character of a simulation calculus based optimisation methods are not appropriate for a simulation based optimisation.

- sufficient computing power

  Simulation based optimisation is typically used when the number of different model configurations is large. This is often accompanied with complex model structures. Both results in considerable quantity of computing time while searching for the optimal model configuration.

Descriptions of established and new simulation based optimisation approaches follow in sections 2.2 and 2.3.

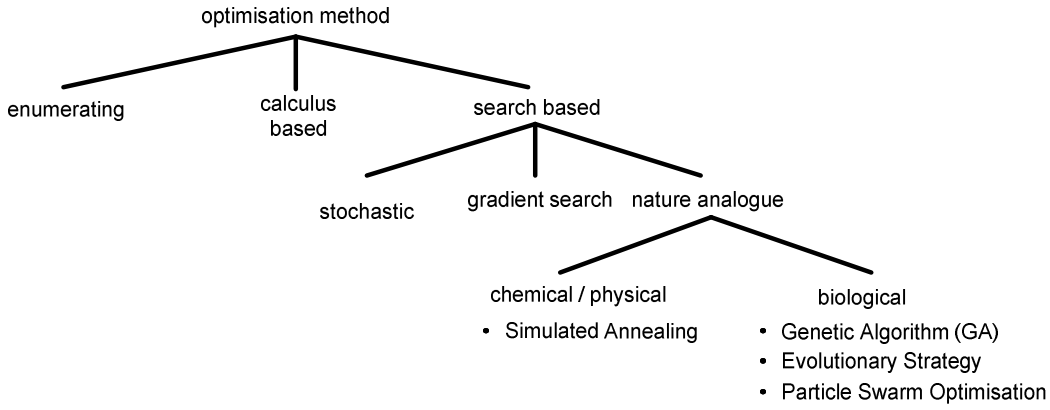


Figure 2.2 Classification of optimisation methods

2.2 Parameter Optimisation

An established approach to simulation based optimisation is simulation based parameter optimisation. The overall goal of this optimisation approach is the identification of improved settings of user selected model parameters under control of performance measures. There is a extensive and varied body of literature on this topic that includes several tutorials, reviews and summaries of the current state of the art (e.g. [4], [6], [14], [32], [55], [56]). Law and Kelton describe in [25] commercial available simulation tools with integrated optimisation techniques using this approach of simulation based parameter optimisation. Figure 2.3 shows a principle example of a simulation based parameter optimisation experiment. The procedure to create an executable model follows the procedure described in figure 2.1. A crucial difference is the detachment of model and model parameters. Based on this detachment the optimisation method is able to alter the model parameter set to improve the result of an objective function. The objective function measures the model performance with current model parameters i.e. improving the objective function result means improving the model performance. Model parameter adjustments are carried out in a loop until a stop criteria is fulfilled. Examples of stop criteria are (i) going below a minimum alteration rate or (ii) exceeding the maximum number of optimisation cycles. The result of a successful optimisation experiment (example criterion (i) fulfilled) is a parameter optimised model.

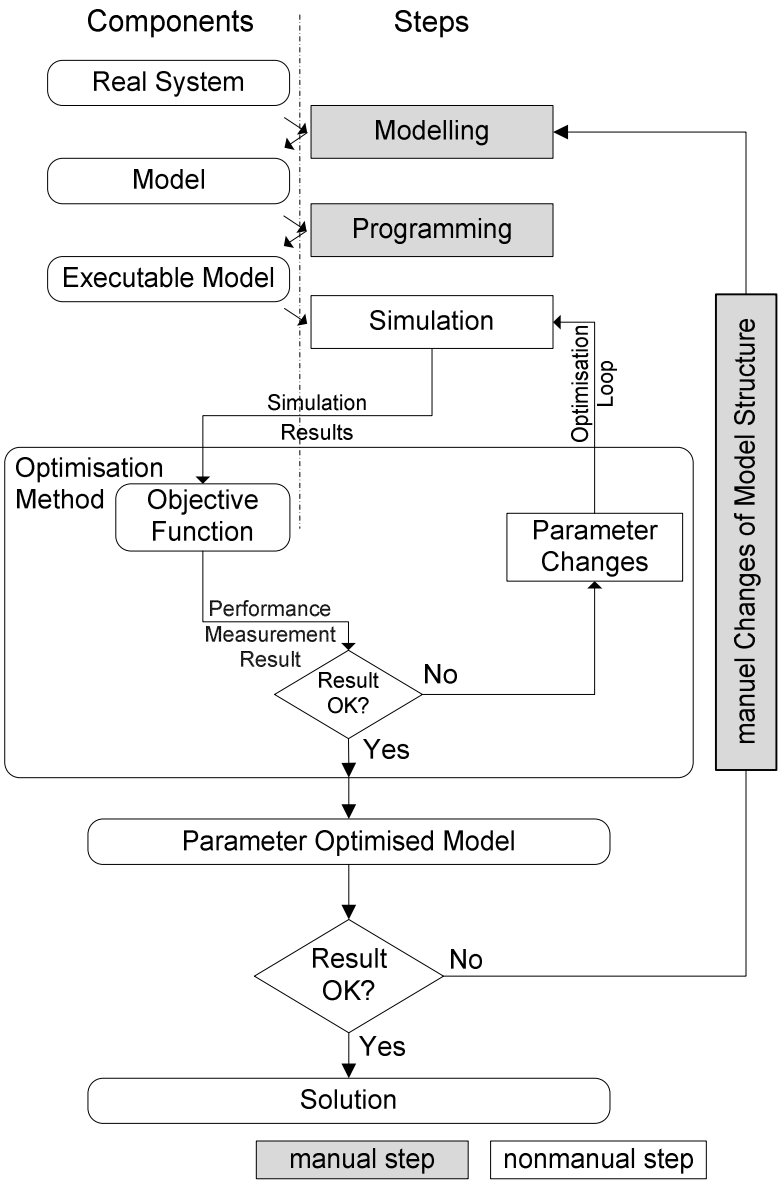


Figure 2.3 An example of a simulation based parameter optimisation experiment

According to [56], a simulation based parameter optimisation problem O with a set of m deterministic model parameters $X = \{x_1, \ldots x_m\}$ can be formally described as follows:

- A parameter set $X = \{x_1, \ldots x_m\}$ has the domain set $D = \{d_1 \ldots d_m\}$
- The multidimensional (one for each parameter) search space S is defined by

  $S = \{s = \{v_1 \ldots v_m\} \mid v_i \in d_i\}$
- A set Y is the output set defined by $Y = \{y_1 \ldots y_n\} = Y(X)$ and estimated by simulation. Simulation experiments are often based on stochastic model properties.

Hence the output set Y is stochastic.

- The objective function F establishes a single stochastic value from stochastic output set $Y : F = F(Y(X)) \rightarrow \Re+$. The result of the objective function is a measure of the current model performance.
- Because of the stochastic nature of Y and consequently of F, an estimation function R, the simulation response function defined by $R(X)=E(F(Y(X)))$, is optimised, i.e. in the scope of this approach it is minimised.
- Depending on optimisation problem and analysis required the exchange of the last two steps, evaluation of objective function F and simulation response function R, can save computational effort. Hence, the simulation response function is defined by $R(X) = E(Y(X))$ and subsequently the objective function by $F(X) = F(R(X))$.

Each parameter set $X_i \in S$ can be seen as a possible solution of O. The optimisation method has to search the search space S to find the parameter set $X_{opt} \in S$ with $E(F(Y(X_{opt}))) \leq E(F(Y(X_i))) \ \forall X_i \in S$. The resulting parameter set X_{opt} is considered the global optimum of O.

This approach is restricted to automated parameter optimisation. It is important to note that automatic structure changes during optimisation are not possible with this approach. Instead, structure changes are carried out manually by an analyst and each manual structure change requires a repetition of the automated parameter optimisation.

2.3 Parameter and Structure Optimisation

The extension of the optimisation approach with the ability to also change model structures to improve system performance is a development of the idea introduced in section 2.2. This extension is mainly directed towards a simulation based structure and parameter optimisation as presented in figure 2.4. The approach of a simulation based parameter and structure optimisation differs in the following extensions or modifications from the simulation based parameter optimisation depicted in figure 2.3:

- An analyst does not generate a single model of the real system. In this case he has to organise a set of models. One way of achieving this is to define a model that describes a set of model variants instead of one single model of the system under analysis. Models that define the creation and interpretation of a set of models are named meta-models. If a model is the abstraction of an aspect of the real world, a meta-model is yet another, super-ordinate abstraction of the model itself. That is when a model describes the behaviour and structure of a real system then a meta-model describes the behaviour and structure of different models that all describe the behaviour and structure of the same real system in a slightly different way.
- The model management organises the set of model structures and provides a model selection method.
- The model selection is controlled by a superior optimisation. The selection method delivers the selected model structure information to a model generator which generates an executable model. The parameter transfer and the simulation match the simulation based parameter optimisation depicted in figure 2.4.
- The objective function receives simulation results to estimate the performance of current model structure and parameters similar to the approach depicted in figure 2.4. Information generated by the model selection method can be additionally used to establish the model performance.
- The optimisation method investigates the search space with simultaneous model parameter and model structure changes without a manual involvement. The intention of the optimisation method is the finding of a model structure and model parameter set where the objective function delivers the global optimum value, in most instances the global minimum.

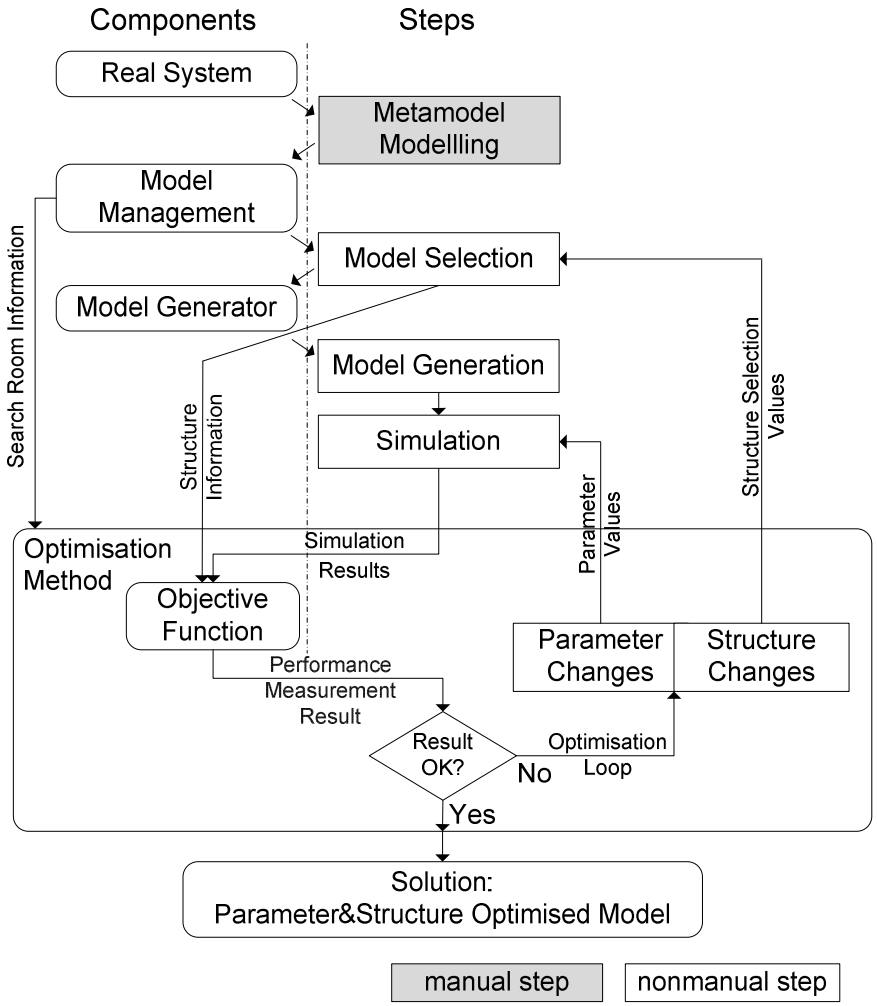


Figure 2.4 Components and steps of a simulation based parameter and structure optimisation experiment

A prerequisite for an optimisation is the definition of a search space. In the approach presented here, the search space is multi-dimensional as a result of the combination of model structure and model parameter variants. During the optimisation loop several points of the search space are examined. Each point defines a model structure with an appropriate parameter set. The extension of the formal description of a simulation based parameter optimisation problem O, defined in section 2.2, to a combined simulation based structure and parameter optimisation leads to O^*:

- The model parameter set X_P and its domain set D_P, in section 2.2 defined as X and D, are extended by structure parameter set X_S and its domain set D_S. The extended set

definitions are: $X^* = X_P \cup X_S = \{x_{P1} \ldots x_{Pm}, x_{S1} \ldots x_{Sn}\}$ and $D^* = D_P \cup D_S = \{d_{P1} \ldots d_{Pm}, d_{S1} \ldots d_{Sn}\}$ with m model parameters in set X_P and n structure parameters in set X_S. The sets X_P and D_P are defined by the current model. The model management has to provide the sets X_S and D_S by analysing the meta-model.

- The multi-dimensional (one for each parameter) search space $S = S_P \cup S_S$ is spanned by sets of model parameter and structure variants.
- The objective function F^* is defined by $F^*(Y(X^*),P(X_S))$ with simulation results $Y(X^*)=Y(X_S \cup X_P)$ and results based on structure related variables $P(X_S)$ which are established during the model selection. Because of the stochastic nature of the simulation results $Y(X^*)$ an estimation function R, the simulation response function, is calculated. The results based on structure related variables $P(X_S)$ are not stochastic. Hence, the simulation response function is defined by $R(Y(X^*))$ and subsequently the objective function by $F^*(R(Y(X^*)), P(X_S))$.

Figure 2.5 depicts the above formal description of a simulation based parameter and structure optimisation framework O^* in a schematic diagram.

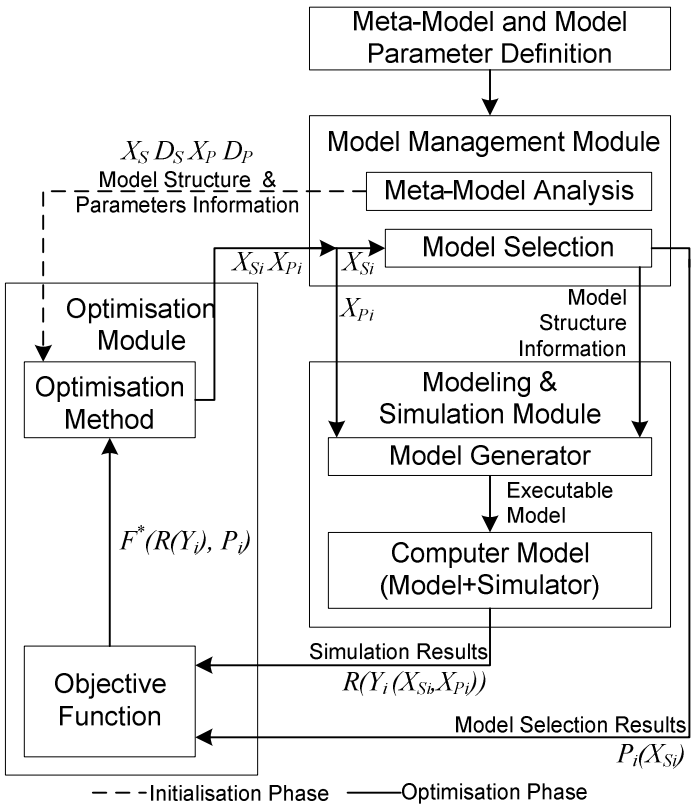


Figure 2.5 Schematic diagram of a simulation based parameter and structure optimisation framework

Further prerequisites of the introduced approach are:

- The modelling and simulation method with support of modular or modular, hierarchical models and a flexible simulation engine are essential parts of the framework. A powerful modelling and simulation method is fundamental in two different aspects: (i) A strict separation between model and simulator are necessary due to the crucial management of a model structure set with a downstream model generator and a model parameter transfer. (ii) A flexible and modular, hierarchical modelling and simulation method can incredible enlarge the application field and ease its use.
- The cooperation between optimisation, model management, and modelling and simulation modules has to be comprehensive. The aim of the cooperation is to establish control of both model parameters and model structures by an optimisation method. The objective function evaluates simulation results but can also incorporate

further information, generated by model management, into the evaluation. The additional parameters can be provided by optional variables, summarised during model selection as described in section 4.2. The search space definition used by the optimisation module is established by the model management module. These information exchanges require comprehensive cooperation between the above modules.

- Using combined simulation based structure and parameter optimisation the number of variants of different system configurations can be considerable higher than in a pure simulation based parameter optimisation and will need more computing power than the approach described in section 2.2.

Through the inclusion of a model management method, the optimisation method can simultaneously control parameter changes as well as model structure changes to find an optimal system configuration. This new approach significantly enhances the application of simulation based optimisation. The extension of the simulation based parameter optimisation by a controllable model management and subsequent automatic model generation is a fundamental idea behind this research.

The modelling and simulation and model management methods take a crucial role in this approach. The description of a discrete event modelling and simulation method, and a model management method based on meta-modelling follow in the next two chapters.

Chapter 3

Discrete Event System Specification and Simulation

After a short, general introduction to modelling and simulation this chapter explains the DEVS formalism. The Classic DEVS formalism will be introduced together with several extensions which are combined to form an Extended Dynamic Structure DEVS (EDSDEVS) approach. The chapter concludes with the introduction of the EDSDEVS formalism. The EDSDEVS modelling and simulation approach with its advanced, modular, hierarchical model definitions and flexible simulation algorithms plays a major role in the new simulation based optimisation approach.

3.1 Introduction

A simulation is the imitation of the behaviour and the structure of a real-world system. The behaviour and the structure of the system are studied by developing a simulation model and performing experiments with it. During an experiment the model is executed within a simulation environment by a simulator. The model is usually created by taking assumptions concerning the function of the system, its attributes and structures. The complete system is split into several entities with relationships defining connections between them. A more complex system can be split in a hierarchical manner i.e. an entity can be segmented into sub-entities which themselves can be again segmented into sub-entities. The entities are expressed in a mathematical, logical or symbolic form. Once developed and validated a model can be used to perform a variety of analysis concerning the real-world process or

system. Analysing experiments can change the behaviour or the attributes of a certain entity, the relationship between entities or sending changed inputs to the model.

It is possible to summarise as follows and as shown in figure 3.1:

- Modelling and simulation is the imitation of a real-world system.
- The model tries to describe real-world behaviour through states, state-transitions and attributes.
- The model tries to describe the real-world structure throughout partitioning into sub-entities. Subject to the modelling formalism, the structure can be defined hierarchically.
- The model interacts with its environment based on inputs and outputs.

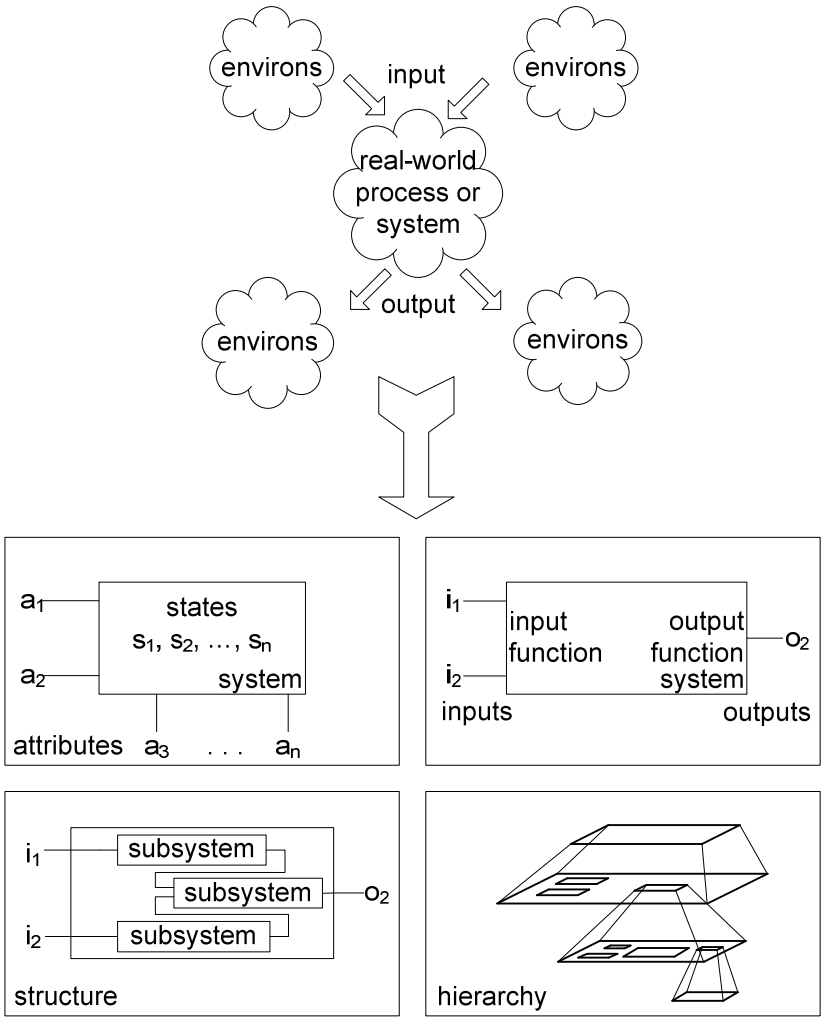


Figure 3.1 A real-world process or system and its model (source [1])

Under some circumstances, a model can be developed based on mathematical methods only e.g. by the use of differential equations, algebraic methods or other mathematical techniques. However, many real world systems are to complex to be modelled using mathematical expressions. In these cases, numerical, computer based modelling and simulation can be used to analyse the behaviour and the structure of real word systems [7].

Many different concepts and methods for modelling and simulation exist. Ören [33] classifies different types of simulation models with several criteria. One of the various possible classifications is to use the two criteria - time change and state change [48]. Discrete event models are a combination of continuous time and discrete state changes as shown in figure 3.2. The choice of whether to use discrete state changes, continuous state changes or a combination of both depends on the characteristics of the system under investigation and the objectives of the study.

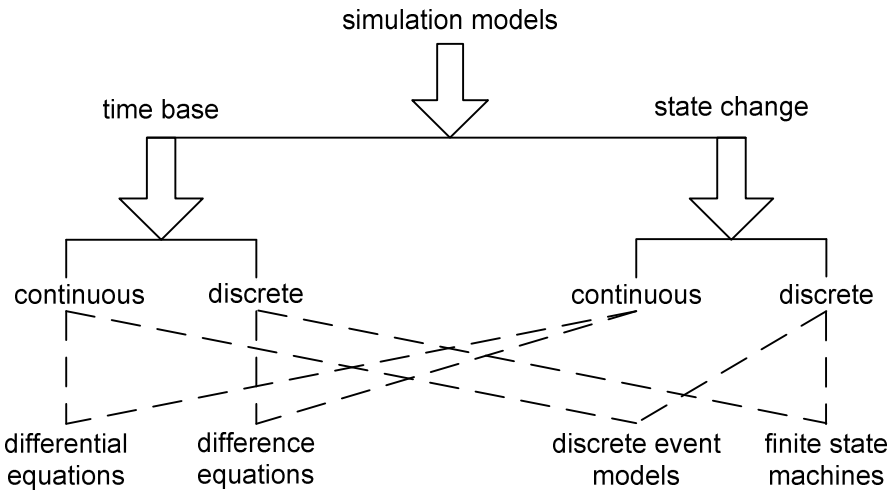


Figure 3.2 Simulation model taxonomy (source [48])

The Discrete Event System Specification (DEVS) is a formalism based on discrete event models. It supports a modular, hierarchical model construction and claimed to be a general and powerful approach in the field of discrete event simulation [66] [67].

For modelling and simulation and particularly with DEVS the term formalism is used with a specific meaning. A modelling formalism can be described by two parts: (i) formal model specification and (ii) simulation algorithms to execute the model [53]. The

formal mathematical specification describes model structure and behaviour. The simulation algorithms specify methods to execute any model that is described in accordance with the formal model specification.

3.2 Discrete Event System Specification

The DEVS formalism was first introduced by Zeigler [68] in the 1970s. In [66] the authors classify this formalism, position and compare it with other, more established modelling and simulation formalisms. Several international research groups are working on the DEVS formalism and are regularly publishing results at the annual DEVS Symposium at Spring Simulation Conferences. Wainer [62] maintains a list of available DEVS tools. The DEVS formalism is, in contrast to other modelling and simulation formalisms, not very widely used in industrial practice. This situation exists despite the fact that the theory is a well-founded, general formalism. It can only be assumed that one reason of the marginal acceptance is the type of available software tools [34].

Since its first publications, in [68] the formalism has been enhanced and many extensions have been introduced. To differentiate among them the original formalism is termed Classic DEVS.

3.2.1 Classic DEVS Modelling

DEVS is a modular, hierarchical modelling and simulation formalism. Every DEVS model can be described by using two different model types, atomic and coupled. Both model types have an identical, clearly defined input and output interface. An atomic model describes the behaviour of a non-decomposable entity via input/output events and event driven state transition functions. A coupled model describes the structure of a more complex model through the aggregation of several entities and their couplings. These entities can be atomic models as well as coupled models. Due to the identical interfaces and the complete encapsulation of a model, a coupled model cannot differentiate between the different model

types of its sub components. A coupled model does not need and does not even have any information about the type of its sub-entities. The internal structure of each sub model is completely encapsulated and separated from its parent. Due the possibility that several entities together create a new entity which itself can be again part of another super-ordinate entity the formalism is termed 'closed under coupling'. Thus, the construction of modular, hierarchical models is possible [66].

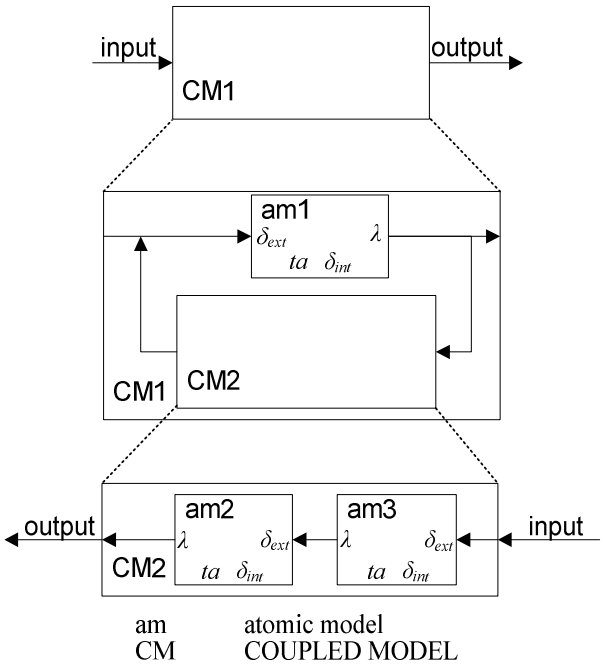


Figure 3.3 DEVS model example

Figure 3.3 shows a DEVS model example:

- Structure description:

  The structure of the real-world system is depicted by the structure of the DEVS model i.e. the aggregation of entities and sub-entities and their directed coupling relations. The top most model i.e. the root model depicts the real-world system with an interface to its environment. This external interface is defined by the input and output ports of the root model. The environment is modelled in an Experimental Frame as described in [11] [66]. An Experimental Frame makes the analysis of the modular, hierarchical model possible, generates input events and analyses the output events. The sub-entities input and output ports are connected over directed couplings

with other sub-entities input and output ports and with the output port of the super-ordinate coupled model, respectively. Each atomic and coupled model has one input and one output port. Depending on source and destination port the coupling relations are named:

- external input coupling (EIC) with the input port of a super-ordinate coupled model as source and one or more sub-entities as destination
- external output coupling (EOC) with the output port of a sub-entity as source and the output port of a super-ordinate coupled model as destination
- internal coupling (IC) with output and input port of sub-entities as source and destination

Example:

The coupled model *CM1* in figure 3.3 is the top most model i.e. the root model. The root model has an external interface with input and output ports to handle or create external input and output events received by or sent to the experimental frame. It contains one atomic model *am1* and one coupled model *CM2*. The coupled model *CM2* consists of two atomic models *am2* and *am3*. As an EIC the input port of *CM1* is connected to the input port of *am1*. As an EOC the output port of *CM1* forwards events sent from the output port of *am1*. ICs are the connections between the output port of *am1* and the input port of *CM2*, output port of *CM2* and the input port of *am1* and output port of *am3* and the input port of *am2*.

- Behaviour description:

The behaviour of a real-world system and sub system, respectively, is depicted by an atomic model and its internal states, input/output events and event driven state transition functions. At its input port it can receive external input events. An input event is handled by an external state transition function. This function can immediately but indirectly induce an internal event and subsequently an internal

transition. With time controlled internal transitions an atomic model can react to time events. Internal events are scheduled by a time advance function and their state transitions are handled by an internal state transition function. After each external and internal event the time advance function is called to schedule the next internal event. With output events send from an output port the atomic model can influence other entities connected to this port or create the output event of the super-ordinate coupled model. Output events are created by an output function which is firstly executed during internal event handling before calling the internal state transition function.

Example:

The atomic model *am1* in figure 3.3 executes the external state transition function δ_{ext} when it receives an input event. After initialisation and after each event handling the next internal event is scheduled with the time advance function *ta*. During the internal event handling by model *am1* the internal state transition function δ_{int} is called. Before the function δ_{int} is called an output event can be created by executing the output function λ.

- Event handling:

All input events are received over the input port regardless of event source and type. All output events are sent over the output port regardless of event type. An event received at an input port of a coupled model is forwarded to the connected sub-entity(s). An event send to an output port of a coupled model by a sub-entity is received and handled by the super-ordinate coupled model. An event send by a sub-entity to one or more sub-entities of the same coupled model is routed by this coupled model from sending output to receiving input port.

Example:

When *CM1* in figure 3.3 receives an event at its input port it is forwarded over the EIC to *am1*. When *CM2* forwards an output event to its output port, the event

is forwarded to the input port of *am1* over the IC. When *am1* generates an output event at its output port this event is forwarded to *CM2* due to an IC and simultaneously it represents an output event of *CM1* due to an EOC.

3.2.2 Formal Concept of Classic DEVS Modelling

The Classic DEVS formal description defines coupled and atomic models as a combination of sets and functions. The description of an atomic model is a 7- tuple [66]:

$AM = (X, Y, S, \delta_{ext}, \delta_{int}, \lambda, ta)$

- X, Y and S specify the sets of discrete inputs, outputs and internal states.
- $\delta_{ext}: Q \times X \rightarrow S$ where $Q = \{(s,e) \mid s \in S, 0<e<t_{next}$, *elapsed time* $e = t - t_{last}\}$

  The external state transition function δ_{ext} handles external input event at time t. It can induce an internal transition with a rescheduling of the time of the next internal event. The time of the external input event is stored in t_{last}.
- $\delta_{int}: S \rightarrow S$

  The internal state transition function δ_{int} can establish a new internal state. The execution of output function λ and internal state transition function δ_{int} is induced by a time driven internal event. The time of an internal event is established by the time advance function *ta*. The time of the internal event is stored in t_{last}.
- $\lambda: S \rightarrow Y$

  The output function λ can generate an output event. If and which output event is generated depends on the internal state S.
- $ta: S \rightarrow \Re_0^+ \cup \infty$

  The time advance function *ta* schedules the time of the next internal event after each state transition.

Figure 3.4 shows the dynamic behaviour of an atomic model. Listing B.1 in appendix B shows a pseudo code skeleton of an atomic model.

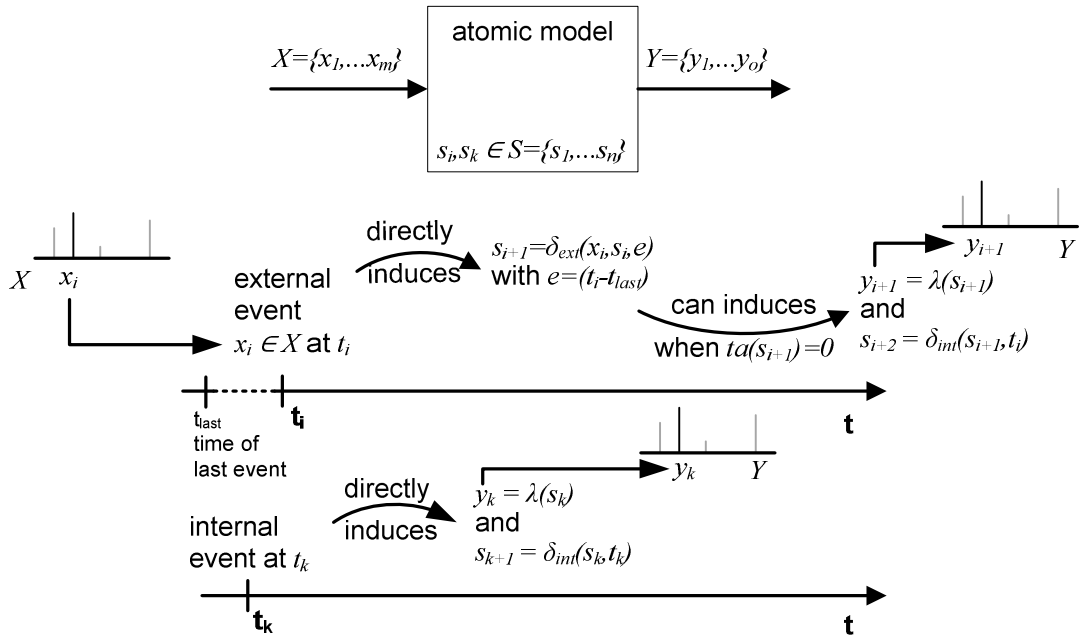


Figure 3.4 Dynamic behaviour of an atomic model

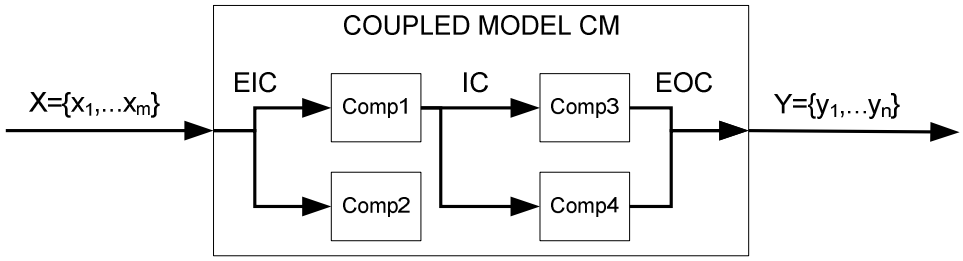
The description of a coupled model is a 9-tuple [66]:

$CM = (d_n, X, Y, D, \{ M_d \}, EIC, EOC, IC, SELECT)$

- d_n specifies the name of the coupled model.
- X and Y specify the sets of discrete inputs and outputs.
- D specifies the set of sub component names.
- $M_d \mid d \in D$

  M_d is the model of the sub component d
- *EIC*, *EOC* and *IC* are the sets of external input, external output and internal couplings.
- The *SELECT* function prioritises concurrent internal events of sub components.

The figure 3.5 depicts the relations of the elements of a Classic DEVS coupled model. Listing B.2 in appendix B shows a pseudo code skeleton of a coupled model.



EIC	= {{CM.X,Comp1.X} {CM.X,Comp2.X}}
IC	= {{Comp1.Y,Comp3.X} {Comp1.Y,Comp4.X}}
EOC	= {{Comp3.Y,CM.Y} {Comp4.Y,CM.Y}}
D	= {"Comp1", "Comp2", "Comp3", "Comp4"}
$\{M_d \mid d \in D\}$	= $\{M_{Comp1}, M_{Comp2}, M_{Comp3}, M_{Comp4}\}$
SELECT	: priority_order(M_{Comp1}, M_{Comp2}, M_{Comp3}, M_{Comp4})

Figure 3.5 Coupled model elements

The Classic DEVS approach supports the specification of behavioural system dynamics in atomic systems and the specification of static component aggregations in coupled systems. It is not possible to describe structural system dynamics at the coupled model level, i.e. the deletion or creation of components and couplings or changes of interfaces, although all necessary structural information is also available during simulation time as is described in section 3.2.3. The only possibility to realise a structural system dynamic is to specify it with logical constructs at the atomic model level. However, this removes the advantages of reusability and model clarity and increases modelling complexity.

3.2.3 Classic DEVS Simulation

Beside the formal definition the second part of the Classic DEVS formalism is the description of abstract simulator algorithms for the execution of DEVS models. The algorithms are named abstract because they are implemented as a general pseudo code. The abstract simulator has a modular, hierarchical structure matching exactly the modular, hierarchical structure of a DEVS model. A DEVS model can be directly transformed into an executable simulator model using abstract simulator elements e.g. as in [48] [66] [67] shown. The abstract simulator approach consists of three different elements namely root coordinator, coordinator and simulator. The structure corresponds to the hierarchical DEVS model

structure except the root coordinator added as the topmost entity. Each atomic model is associated with a simulator element and each coupled model is associated with a coordinator element.

Figure 3.6 shows the transformation of a DEVS model to an executable simulation model using associated abstract simulator elements. The two coupled models *CM1* and *CM2* are mapped to two coordinator elements. The three atomic models *am1...am3* are mapped to simulator elements.

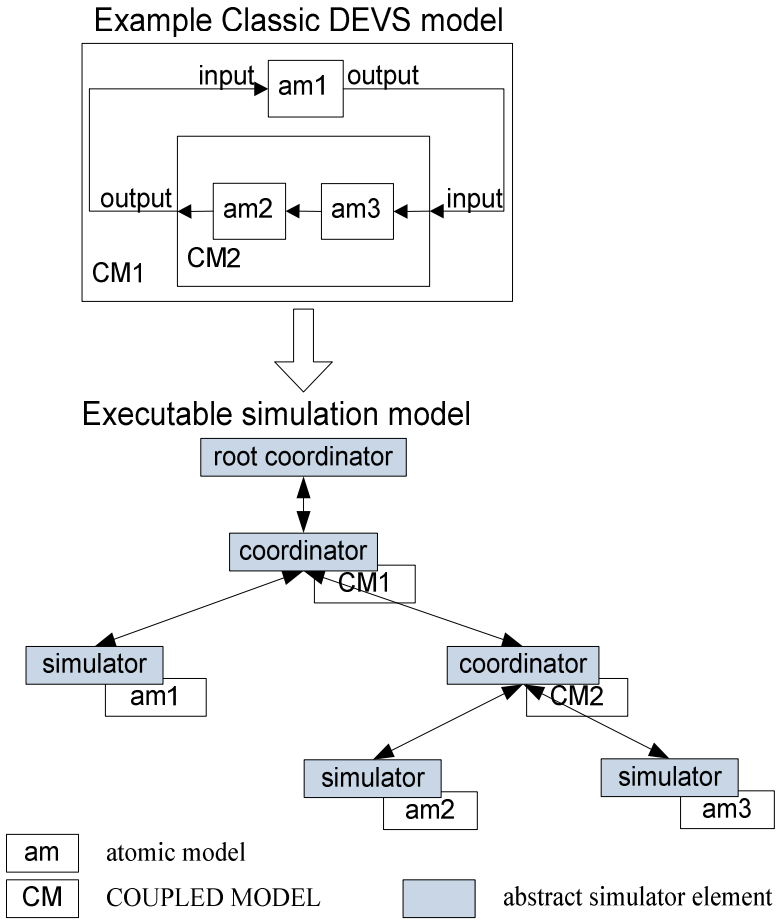


Figure 3.6 An example of a Classic DEVS model with associated abstract simulator elements

The communication between *root coordinator*, *coordinator* and *simulator* instances is message based. On top of the hierarchy the *root coordinator* initiates, controls and ends a simulation cycle with different messages. It holds the simulation clock. Each coupled model is associated to a *coordinator* instance. The *coordinator* instance forwards messages to its subordinated *coordinator* and/or *simulator* instances. It holds the minimum time of the next

internal transition event of its sub components in t_{next}. Each atomic model is associated with a *simulator* instance. It holds the time of its own next internal events in t_{next}. It is important to note that both *coordinator* and *simulator* instances have the same interfaces and receive the same messages. Hence, a super-ordinate coordinator does not have to distinguish the type of subordinate instances.

With this concept one prerequisite of a parameter and structure optimisation approach as introduced in section 2.3 is fulfilled. The modular modelling and flexible simulation play a crucial role in model management and subsequent model generation.

Furthermore this concept enables that the modular hierarchical structure of a model remains an unchanged part of the computational model during simulation runtime. The preservation of the model structure is an essential prerequisite to the dynamic structure modelling and simulation concept introduced later in this chapter. This dynamic structure modelling and simulation concept fulfils another prerequisite of parameter and structure optimisation approach.

Figure 3.7 depicts the structure of a Classic DEVS model with the corresponding abstract simulator instances. Moreover, the figure presents the different messages types passed between the several instances of abstract simulator elements and the subsequent DEVS model function calls. Because of complexity and clarity selected situations are shown in sections:

i. (Figure 3.7a) initialisation phase with i-message handling:

   During the initialisation phase model component's init functions are called because of an i-message handling.

ii. (Figure 3.7b) *-message handling created due to internal event of model *am3* with a subsequent x-message within the same coupled model:

   The root coordinator advances the simulation clock and a *-message is firstly created. The message is sent to the successor coordinator instance of coupled model *CM1*. This coordinator instance determines that the sub component *CM2* is

responsible for handling this event. Hence, the event is forwarded to the successor coordinator instance of *CM2*. The coordinator instance determines that one of its sub components scheduled the event. The simulator instance of model *am3* initiates the internal message handling. Due to the current internal state of *am3* an output message is generated. With the internal coupling *am2-am3* the message is received as an x-message by simulator instance/model *am2*.

iii. (Figure 3.7c) *-message handling created due to an internal event of model *am1* with a subsequent x-message at different model levels:

The beginning of the message handling is similar to ii except the generated output message is forwarded to another model level over internal and external input couplings.

iv. (Figure 3.7d) *-message handling created due to concurrent internal events of models *am2* and *am3*:

The root coordinator advances the simulation clock and a *-message is firstly created. The message is sent to the successor coordinator instance of coupled model *CM1*. This coordinator instance determines that the sub component *CM2* is responsible for handling this event. Hence, the event is forwarded to the successor coordinator instance of *CM2*. The coordinator instance determines that two sub components scheduled the event. The coordinator instance will then call the select() function to decide which sub components has a higher priority and forward the message to the appropriate simulator instance. The simulator instance calls the model functions λ and δ_{int}. A result of calling λ could be a y-message sent back to the subordinate coodinator instance of *CM2*.

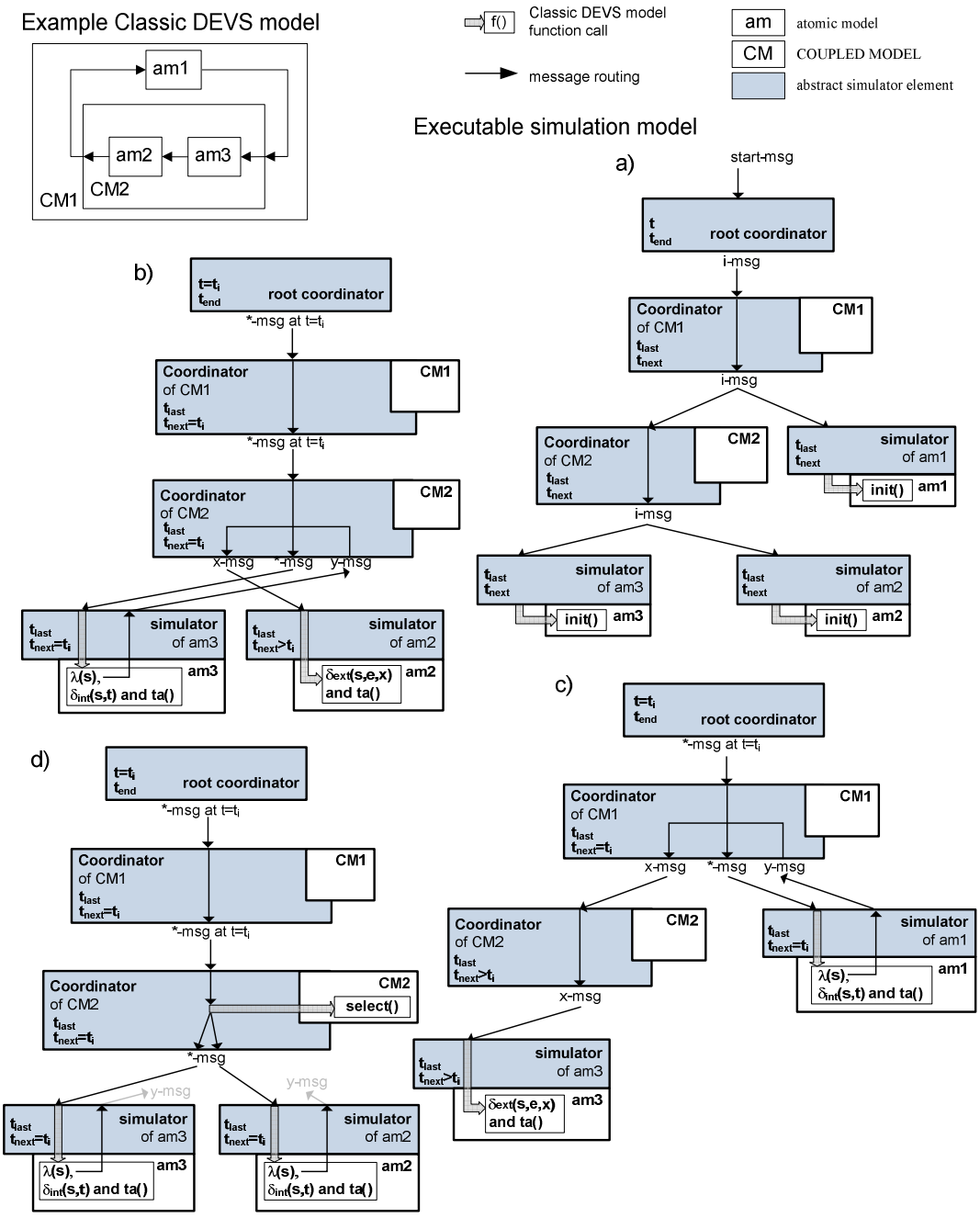


Figure 3.7 An example of a Classic DEVS model with associated abstract simulator elements, messages and model function calls during initialisation and simulation phases

The execution of the simulation model can be subdivided into two phases: initialisation phase and simulation phase. Each phase is started and proceeded by several messages passed between root coordinator, coordinator and simulator instances:

- The initialisation phase starts with an initialisation message (i-msg) generated by the root coordinator. This message is redirected and handled by each coordinator

instance and handled by each simulator instance, respectively. Each simulator instance initialises the internal states *S* of the associated atomic model and estimates the time of the first next internal event t_{next}. Each coordinator estimates the minimum time of the first next internal events of all sub components. Due to the hierarchical structure of the simulation model the root coordinator instance gets the minimum time of the first internal event of all model components from its direct successor coordinator after a complete i-msg handling.

- The simulation phase is started with the first *- message (*-msg) at the minimum time of next internal event t_{next} estimated by the root coordinator as described above. The consequence of a *-message are subsequent input and output messages (x and y-msg). All simulator instances which received a *- or x-message can change the time of their next internal event t_{next}. All coordinator instances redirecting a *-, x- or y-message estimates the minimum time of next internal events of their sub components. Due to the hierarchical structure of the simulation model the root coordinator instance gets the minimum time of next internal events after a complete *-message handling. The root coordinator instance advances the simulation clock to that time and repeats the complete process by sending the next *-message. Advancing the simulation clock and message handling is repeated in a loop until the simulation end time t_{end} is reached or exceeded.

The different message types created and handled during initialisation and simulation phase have the following characteristics:

- start-msg(tend)
  The start-message is created and sent only once. It starts the simulation model execution with the generation of an i-message.
- i-msg()
  The i-message starts the model component initialisation at time *t=0*. The root coordinator instance sends one i-message to its direct successor coordinator

instance to initialise all model and simulation components. Each coordinator instance sends further i-messages to its sub components.

- *-msg(t)

  A *-message received by a simulator instance starts the processing of an internal event by calling the output function λ, internal state transition function δ_{int} and time advance function *ta* of the corresponding atomic model. The time of the *-message is stored in t_{last} of the simulator instance. The output of function λ is sent up to the parent coordinator instance as a y-message. The final execution of function *ta* can cause a new time of the next internal event depending on the internal state *S* of the atomic model and stored in t_{next} of the simulator instance.

  A *-message received by a coordinator instance is sent to the successor simulator or coordinator instance with the appropriate time t_{next}. For this purpose the coordinator instance compares the actual simulation time with a list of t_{next}-instance pairs. The time-instance-pairs of all next internal events of all sub components are stored in an event chain of the coordinator instance. Concurrent internal events i.e. different sub components have the same t_{next} are resolved by the *select* function of the parent coupled model. After a complete handling of the *-message the coordinator instance estimates the minimum time of next internal events of all sub components and stores it in t_{next}.

- x-msg(t, x)

  An x-message received by a simulator instance calls the external state transition function δ_{ext} and time advance function *ta* of the corresponding atomic model. The time of the x-message is stored in t_{last} of the simulator instance. The final execution of function *ta* can cause a new time of next internal event stored in t_{next} of the simulator instance.

  An x-message received by a coordinator instance is redirected to all sub components with an appropriate EIC. After a complete x-message handling the

coordinator instance estimates the minimum time of next internal events of all sub components and stores it in t_{next}.

- y-msg(t, y)

  The y-message is created by an atomic model/simulator instance. It is routed by the super-ordinate coordinator instance according the coupling relations to other successor simulator and/or coordinator instances or to the parent of the super-ordinate coordinator instance. Receiving simulator or coordinator instances get this message as an x-message.

Listings B.3, B.4 and B.5 in appendix B show pseudo codes of Classic DEVS root coordinator, coordinator and simulator.

3.3 DEVS Extensions

Extensions of the Classic DEVS formalism expand the classes of system models that can be represented by DEVS. Several DEVS extension are introduced e.g. in [9] [38] [48] [60] [62] and [66]. At the regular DEVS symposium held at the annual Spring Simulation Multi Conferences the current development of DEVS, DEVS extensions and DEVS related developments are published. An incomplete list of DEVS extensions recently presented are:

- DEVS with Ports

  The port extension adds additional input and output ports to atomic and coupled models. The approach is introduced later in more detail.

- Parallel DEVS

  Parallel DEVS (PDEVS) considers concurrent transition events. The approach is introduced later in more detail.

- Dynamic Structure DEVS

  Dynamic Structure DEVS (DSDEVS) enables model structure changes during a simulation run. Several partial very different approaches exist. Dynamic structure extensions introduced by Barros [9] and Pawletta et.al. [38] preserve the general

structure of Classic DEVS modelling and simulation with additions to coupled model definitions but unchanged atomic model definitions. Other dynamic structure extensions e.g. Uhrmacher with an agent based DEVS [60] introduce more extensive modifications. The approach of Pawletta et.al. is introduced in more detail in section 3.3.3.

- Symbolic DEVS

  It represents occurring events in a symbolic definition [12]. In conventional DEVS, the time base, its operations and relations are performed with real numbers. In Symbolic DEVS, the objective is to explore multiple model behaviours simultaneously e.g. with a symbolic result of the time advance function [66].

- Real Time DEVS

  The DEVS model is developed in a conventional simulation environment. But it is executed in real time rather than in model time. The time advance function delivers time intervals rather than single values. The interval allows uncertainty when an internal event has to take place.

- Fuzzy DEVS

  Provides another possibility to enable uncertainty into the model set and model function definitions.

The next sections introduce three DEVS extensions in more detail. The chosen extensions are used as a basis of the subsequent unifying DEVS formalism introduced as a key element of this research.

3.3.1 DEVS with Ports

The introduction of ports into the Classic DEVS formalism makes modelling easier and the representation of information flow more clearly [66]. In Classic DEVS each model has only a single input and a single output port. All events are received and sent over these ports. With the port extension, a model has several input and output ports each dedicated for a

specific employment i.e. event type. A model can have several output ports which can be connected to input ports of other models as shown in figure 3.8. Hence, each event can use a dedicated, well defined routing path. The modelling becomes more structured; a model can become clearer and better understandable through differentiated interfaces.

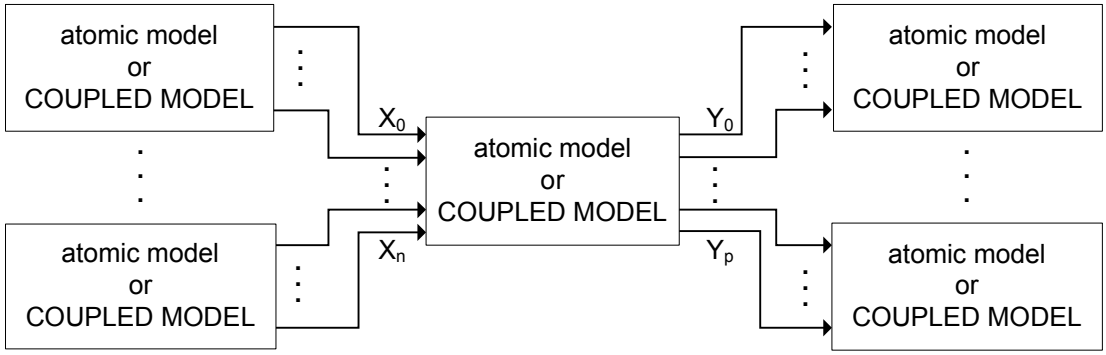


Figure 3.8 Models with multiple input and output ports

The formal description of Classic DEVS with Ports largely remains the same except the extended definitions of *X, Y* for atomic and coupled models [66]:

$X = \{(p,v) \mid p \in InputPorts,\ v \in X_p\}$

$Y = \{(p,v) \mid p \in OutputPorts,\ v \in Y_p\}$

- p is the input or output port of the model
- v is a discrete value
- X_p and Y_p specify the sets of discrete inputs and outputs at port p

Whereas in Classic DEVS the coupling definitions consist of a sub model name as destination and source, respectively, for EIC and EOC and a pair of sub model names for IC the port extension necessitate a coupling definition extension, too:

- $EIC = \{ (input\_port, d.input\_port) \mid input\_port \in InputPorts, d \in D,$

  $d.input\_port \in InputPorts\ of\ M_d \}$

  The external input coupling definition of a coupled model is a set of pairs of an input port name of the coupled model itself and an input port name of the destination sub model.

- $IC = \{ (d_i.output\_port, d_k.input\_port) \mid d_i, d_k \in D, d_i.output\_port \in OutputPorts\ of\ M_{d_i}, d_k.input\_port \in InputPorts\ of\ M_{d_k}, i<>k \}$

  The internal coupling definition is a set of pairs of an output port name and an input port name of sub models.

- $EOC = \{ (d.output\_port, output\_port) \mid d.output\_port \in OutputPorts\ of\ M_d, d \in D, output\_port \in OutputPorts \}$

  The external output coupling definition of a coupled model is a set of pairs of an output port name of source sub component and an output port name of the coupled model itself.

Listings B.6, B.7 and B.8 in appendix B show pseudo codes of an example Classic DEVS with Ports atomic model and pseudo codes of simulator and coordinator. Differences to the Classic DEVS pendants are marked in bold face type.

3.3.2 Parallel DEVS

Parallel DEVS (PDEVS) was introduced by Chow and Zeigler [13]. It adds new elements and functions to the Classic DEVS formalism. It allows all imminent components to be activated and enables sending their output to other components at the same time concurrently. Multiple outputs are combined in a bag which is sent as a whole to a model's external state transition function. A bag is similar to a set, containing an unordered set of elements, but allows multiple occurrences of an element. In Classic DEVS by contrast events are handled individually. In PDEVS during the *-message handling firstly all outputs are established before calling external and internal state transition functions. Each receiving component is responsible for examining and interpreting its combined inputs in the correct order. PDEVS gives the atomic model more control over the handling order of concurrent external and internal events. In Classic DEVS a super-ordinate component, the coupled model, is responsible for the execution order of concurrent internal events of different sub

components using the *select* function. In PDEVS the order of simultaneous events is locally controllable at atomic model level with an additional, third state transition function, the confluent transition function δ_{con}. Hence, it merges the decision logic of execution order of concurrent events with the event handling functions at same level. Apart from that, there is no difference in the principle of event handling to that described in section 3.2.

According to the extensions of PDEVS an atomic model is defined by the following 8- tuple [13]:

$AM = (X, Y, S, \delta_{ext}, \delta_{int}, \delta_{con}, \lambda, ta)$

- X, Y and S specify the sets of discrete input events, output events and sequential states.
- δ_{ext}: $Q \times X^b \rightarrow S$ where X^b is a bag covering elements of X and $Q = \{ (s,e) \mid s \in S, 0<e<t_{next}, \text{ elapsed time } e = t - t_{last} \}$

  The external state transition function δ_{ext} handles a bag covering external inputs $X^b = \{x_i \mid x_i \in X\}$.
- δ_{int}: $S \rightarrow S$

  The internal state transition function δ_{int} establishes a new internal state. The execution of output function λ and internal transition function δ_{int} is induced by a time driven internal event. The time of an internal event is established by the time advance function *ta*.
- δ_{con}: $S \times X^b \rightarrow S$

  The confluent transition function δ_{con} handles the execution sequence of δ_{int} and δ_{ext} functions in case of concurrent external and internal events.
  - The definition $\delta_{con}(s, X^b) = \delta_{ext}(\delta_{int}(s), 0, X^b)$ with $\delta_{ext}(s, e, X^b)$ of the confluent transition function is equivalent to the Classic DEVS behaviour with a higher prioritised internal event handling.

- The alternative defintion $\delta_{con}(s, X^b) = \delta_{int}(\delta_{ext}(s, ta(s), X^b))$ with $\delta_{int}(s)$ of the confluent function firstly handles external events.
- The execution of the confluent function with an empty bag $\delta_{con}(s, null)$ calls directly the internal transition function δ_{int}.

- $\lambda: S \rightarrow Y^b$ where Y^b is a bag covering elements of Y

  The output function λ can generate a bag covering outputs $Y^b = \{ y_i \mid y_i \in Y \}$. The generated output depends on the internal state S.

- $ta: S \rightarrow \Re_0^+ \cup \infty$

  The time advance function *ta* schedules the time of the next internal event after each state transition.

The figure 3.9 shows the dynamic behaviour of an atomic PDEVS model in a situation with concurrent external and internal events. Due to the concurrent events the confluent transition function δ_{con} is called. Depending on the specific implementation of function δ_{con} sequence a) or sequence b) is executed.

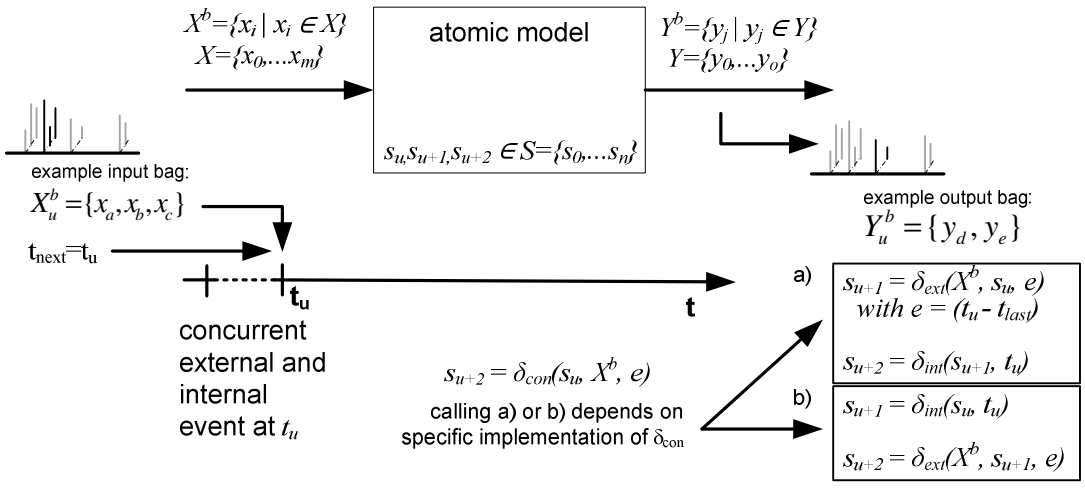


Figure 3.9 Dynamic behaviour of an atomic PDEVS model

The definition of a coupled model for PDEVS is the same as for Classic DEVS except for the absence of the *select* function [13]:

$CM = (d_n, X, Y, D, \{ M_d \}, EIC, EOC, IC)$

The generation of an executable PDEVS model is carried out similarly to Classic DEVS i.e. the same coupling of atomic models with simulator instances and coupled models with coordinator instances and the perpetuation of the original hierarchical model structure. Listings B.9 and B.10 in appendix B show pseudo codes of an example PDEVS atomic model and a PDEVS simulator. Differences to the Classic DEVS pendants are marked in bold face type.

3.3.3 Dynamic Structure DEVS

Several approaches extend the Classic DEVS to Dynamic Structure DEVS (DSDEVS). Barros [9] [10] and Pawletta et.al. [42] introduce two DSDEVS variants with an extension of the coupled model definition while the atomic model definition remains unchanged. With theses extensions the coupled model is able to change its structure during simulation time. Uhrmacher et.al. [60] introduce an agent based approach. It defines extensions for both atomic and coupled systems. Another approach is Cell-DEVS, a combination of cellular automata with the DEVS formalism where each cell consists of a single DEVS model [63].

The different types of extensions are carried out due to different application fields or problem definitions e.g. a typical Cell-DEVS application field is social and environmental modelling and simulation. The approaches of Barros and Pawletta are extending the classic formalism without changing its overall principle and thus the general application field of Classic DEVS. This research is restricted to and continues the research of Pawletta. This DSDEVS approach is introduced in detail in the following.

DSDEVS by Pawletta enables several types of structural dynamics:

- creation, destruction, cloning and replacement of sub components
- exchange of a sub component between two coupled models
- changing coupling definitions of a coupled system

Figure 3.10 shows an example of structure changes, the creation of a sub model with an additional extension of the coupling definition.

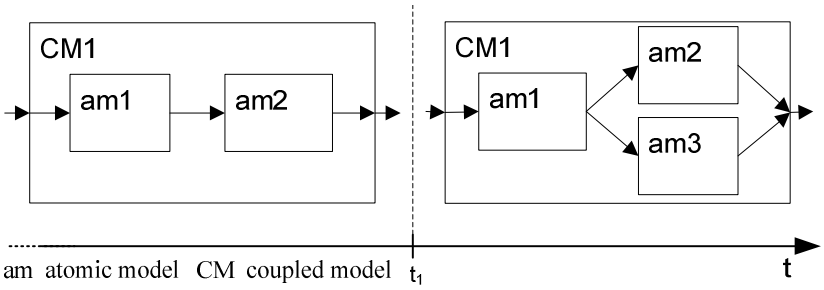


Figure 3.10 Examples of structure changes at coupled model level

Pawletta et.al. have introduced an extension of Classic DEVS to enable structure variability during simulation time [38] ... [45] firstly named Variable Structure DEVS. To avoid name and abbreviation confusions the name of this approach was changed to Dynamic Structure DEVS (DSDEVS) in later publications [34] et seqq. The approach extends the coupled model definition but the atomic model definition stays unchanged. During the simulation time a coupled model can change its structures. Each structure can be seen as a structure state s_i with $s_0, s_1, ...,s_n \in S_{DS}$. A single structure state s_i describes the structure relevant elements of a coupled model i.e. it defines sub components with their couplings, the sets of input and output events together with the concurrent internal event handling function *select*. A structural change of a coupled model means the modification of the current structure state. Additionally a structural state set H_{DS} can store further structure information e.g. the number of structure changes at the present time or the current structure number. External or internal events, handled by the additional state transition functions $\delta_{x\&s}$ and δ_{int} at coupled model level, induce structure state changes and as a result model structure changes. This dynamic structure extension of Classic DEVS was developed with a regard to hybrid systems, i.e. systems with continuous and discrete event dynamics. In the following only the relevant aspects for discrete event systems are taken into account.

A DSDEVS coupled model is defined by the following 6-tuple [38]:

$$CM_{DS} = (d_{ds}, S_{DS}, \delta_{x\&s}, \delta_{int}, \lambda, ta)$$

- d_{ds} specifies the name of the coupled model.

- According to the above definition of a coupled model, its structure consists of sets of sub components and coupling relations. Structure changes means modifications of these sets. Obviously, the sets of sub systems and coupling relations could be interpreted as a structure state. The set of sequential structure states $\{s_0, s_1, ...,s_n\} = S_{DS}$ defines all structure variants of the variable structure coupled model CM_{DS}. Structure state changes can be induced by handling external or internal events of the coupled model itself or by state events i.e. output events of subordinated components. A structure state is defined by a 9-tuple:

  $s_i = (X, Y, H_{DS}, D, \{ M_d \}, EIC, EOC, IC, select)$

  - X and Y specify the sets of discrete input and output events. The sets exactly match the sets X and Y in Classic DEVS.
  - The set H_{DS} represents additional structure related state variables. They are equivalent to the state set S of an atomic model.
  - D specifies the set of sub component names.
  - $M_d \mid d \in D$

    M_d is the model of the sub component d of the coupled model CM_{DS}. The set $\{ M_d \}$ defines all sub components of CM_{DS}.
  - EIC, EOC and IC are the external input, external output and internal couplings.
  - The function *select* prioritises concurrent internal events of the coupled model itself and its sub components.

- $\delta_{x\&s}$: $Q_{DS} \times X \rightarrow H_{DS}$ where $Q_{DS} = \{(h,e) \mid h \in H_{DS}, 0<e<t_{next}, \text{elapsed time } e= t-t_{last}\}$

  The external and state transition function $\delta_{x\&s}$ handles external input events and state events i.e. output events of sub components. However it is unreasonable to make changes in the set of sub components or the coupling relations by this function directly. This could lead to ambiguous event handling because external events could

simultaneously influence the dynamic of sub components and the structure state. Consequently the $\delta_{x\&s}$ function is only allowed to modify structure related state variables in the set H_{DS}. However, it can induce a structure state change i.e. a change of the model structure by scheduling an immediate internal event.

- δ_{int}: $S_{DS} \rightarrow S_{DS}$

  The internal transition function δ_{int} can change the structure state s_i to s_{i+1} and as a result induce a structure change of CM_{DS}. The execution of output function λ and internal transition function δ_{int} is induced by a time driven internal event. The time of an internal event is established by the time advance function *ta*.

- λ: $S_{DS} \rightarrow Y$

  The output function λ can generate output events.

- *ta*: $S_{DS} \rightarrow \Re_0^+ \cup \infty$

  As with the dynamic of atomic models, internal events are scheduled by the time advance function *ta.* After each state transition the next internal event is established by the time advance function.

The dynamic behaviour of an atomic model is identical to the behaviour in Classic DEVS. Figure 3.11 shows the dynamic behaviour of a variable structure coupled model. The figure depicts two external input events and one internal event. Reasons for an input event handling can be an external input event at the input port of the coupled model itself or an external output event at the output port of a sub component M_d of the coupled model. The handling of both events by the coupled model is identically. As a result of an event the structure related state variable set H_{DS} can be changed and with the concluding call of the time advance function an immediate internal event can be induced. An internal event is handled by a coupled model similar to the internal event handling of an atomic model, i.e. the event handling can induce a change of the structure state set S_{DS}, and in this case a change in the set of sub components $\{M_d\}$ and/or the coupling sets *EIC*, *IC* and *EOC*.

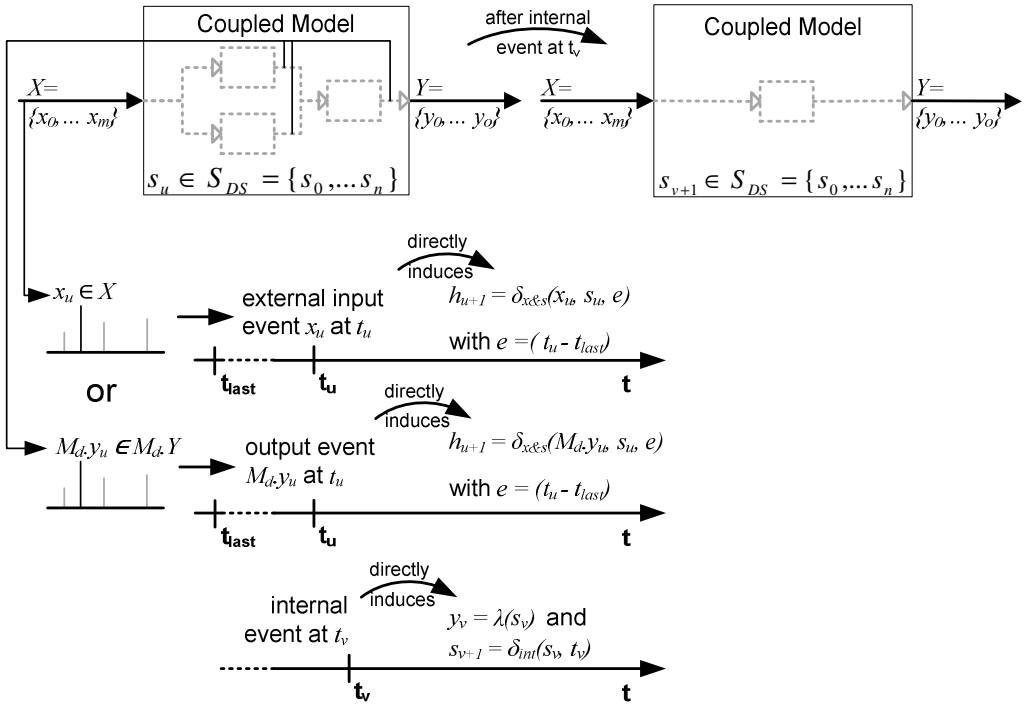


Figure 3.11 Dynamic behaviour of a coupled DSDEVS model

Examples of sequential model structure changes are shown in figure 3.12 a-d. The following definitions of the structure state set describe the insert and change of sub components and couplings as a result of internal events and changes of the sequential structure state set $s_i \in S_{DS}$ by the function δ_{int}. The subsets *X, Y* and H_{DS} and the *select* function of a structure state $s_i \in S_{DS}$ will not be detailed.

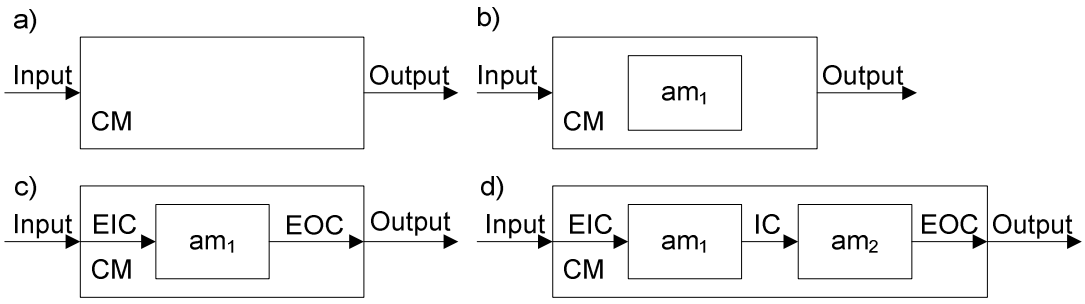


Figure 3.12 Examples of sequential structure changes of a coupled model

a) Figure 3.12a depicts a coupled model *CM* without sub components.

   D, { M_d }, EIC, EOC and *IC* are empty sets

b) In figure 3.12b the coupled model contains one sub component, the atomic model am_1, created as a result of the handling of an internal structure event i.e. the execution of function δ_{int}.

$D = \{ am_1 \}$

$M_d = \{ M_{am_1} \}$

EIC, EOC and *IC* are empty sets

c) Figure 3.12c depicts external input and output couplings created as a result of the handling of an internal structure event i.e. the execution of function δ_{int}.

$D = \{ am_1 \}$

$M_d = \{ M_{am_1} \}$

$EIC = \{ (CM.Input, am_1.Input) \}$

$EOC = \{ (am_1.Output, CM.Output) \}$

IC is an empty set

d) Figure 3.12d depicts the insert of sub component am_2 and the change/creation of several couplings as a result of the handling of an internal structure event i.e. the execution of function δ_{int}.

$D = \{ am_1, am_2 \}$

$M_d = \{ M_{am_1}, M_{am_2} \}$

$EIC = \{ (CM.Input, am_1.Input) \}$

$EOC = \{ (am_2.Output, CM.Output) \}$

$IC = \{ (am_1.Output, am_2.Input) \}$

3.4 Extended Dynamic Structure DEVS

Sections 3.2 and 3.3 introduced the Classic DEVS formalism and several DEVS extensions. Every extension has its advantages and widens the application field of DEVS in a different direction, PDEVS generalises the specification and handling of concurrent events, DEVS with Ports enables a more structured modelling and DSDEVS introduces dynamic structure

changes at coupled model level during simulation time and significantly eases the modelling of larger real systems. The extensions have one joint attribute: they are based on the Classic DEVS formalism. Hence, the decision on one DEVS extension inhibits the use of advantages of another one. This principle leads to the idea of a merging formalism to combine the advantages of different approaches and widen the application field of the resulting formalism. In [66] a first step into this direction is undertaken, the introduced PDEVS formalism is a combination of the original PDEVS and DEVS with Ports. Further steps into this direction are not known. The Extended Dynamic Structure DEVS (EDSDEVS) combines Classic DEVS with the extensions: PDEVS, DSDEVS and DEVS with Ports. The fusion results in a DEVS formalism with the following main characteristics:

- Formal model description by sets and functions
- Exact definition of simulation algorithms
- Modular, hierarchical and dynamic structure modelling and simulation formalism
- Dynamic behaviour description at atomic model level
- Dynamic structure description at coupled model level
- Exact behaviour definition at critical situations with concurrent events
- Substantial similarity between real system and model

The next section introduces the formal concept of EDSDEVS modelling with formal descriptions and dynamic behaviour of atomic and coupled models. Section 3.4.2 goes into detail of the EDSDEVS simulation concept with abstract simulator algorithms, message handling and model function calls.

3.4.1 Formal Concept of EDSDEVS Modelling

The EDSDEVS formal descriptions of coupled and atomic models as a combination of sets and functions are similar structured as the Classic DEVS formal description as introduced in section 3.2.2.

An atomic EDSDEVS model is a fusion of PDEVS with DEVS with Port atomic model definitions. The atomic EDSDEVS model AM_{EDS} is defined as an 8- tuple:

$AM_{EDS} = (X, Y, S, \delta_{ext}, \delta_{int}, \delta_{con}, \lambda, ta)$

- $X = \{(p,v) \mid p \in InputPorts, v \in X_p\}$

  $Y = \{(p,v) \mid p \in OutputPorts, v \in Y_p\}$

  The definitions of both sets are identical to the definitions in DEVS with Ports as introduced in section 3.3.1.

- S specifies the set of internal states and is identical to internal state set S of an atomic Classic DEVS model.

- $\delta_{ext}: Q \times X^b \rightarrow S$ with $X^b = \{x_i \mid x_i = (p,v), p \in InputPorts, v \in X_p\}$ and

  $Q = \{(s,e) \mid s \in S, 0 < e < t_{next}, \text{elapsed time } e = t - t_{last}\}$

  The external state transition function δ_{ext} handles a bag covering external inputs. Each input consists of a pair of a discrete input $v \in X_p$ and an input port $p \in InputPorts$. The set X_P is the set of discrete inputs at port p and $InputPorts$ is the set of input ports of model AM. The function δ_{ext} can induce an internal event with a rescheduling of the time of the next internal event.

  This extended definition of δ_{ext} is a fusion of the δ_{ext} definitions of PDEVS and DEVS with Port.

- $\delta_{int}: S \rightarrow S$

  The internal state transition function δ_{int} can establish a new internal state. The execution of output function λ and internal state transition function δ_{int} is induced by a time driven internal event. The time of an internal event is established by the time advance function ta.

  The definition is identical to definition in Classic DEVS.

- $\delta_{con}: S \times X^b \rightarrow S$

The confluent transition function δ_{con} handles the execution order of δ_{int} and δ_{ext} functions during concurrent external and internal events. In spite of the same function signature $\delta_{con}(s, X^b)$ the parameter X^b is different to that in the PDEVS definition as described in section 3.3.2. Anyhow the three δ_{con} definitions also apply here.

This extended definition of δ_{con} is based on the PDEVS δ_{con} function definition. Unlike in PDEVS the function has to handle a bag covering inputs. Each input consists of a pair of discrete input and input port.

- $\lambda: S \rightarrow Y^b$ with $Y^b = \{y_i \mid y_i = (p, v),\ p \in OutputPorts, v \in Y_p\}$

  The output function λ can generate a bag covering outputs Y^b. In spite of the same function signature $Y^b = \lambda(s)$ the function result Y^b is different to that in the PDEVS definition as described in section 3.3.2. The function result is a bag covering outputs $Y^b=\{ y_i \mid y_i = (p, v) \}$ each consisting of a pair of discrete output $v \in Y_p$ and output port $p \in OutputPorts$. The set Y_P is the set of discrete outputs at port p and *OutputPorts* is the set of output ports of model *AM*. If and which outputs are generated depends on the internal state *S*.

  This extended definition of λ is based on the PDEVS λ function definition. Unlike in PDEVS the function generates a bag covering outputs each consisting of pairs of discrete output and output port as introduced in DEVS with Ports.

- $ta: S \rightarrow \Re_0^+ \cup \infty$

  The time advance function *ta* schedules the time of the next internal event after each state transition. The definition is identical to the definition in Classic DEVS as introduced in section 3.2.2.

The figure 3.13 shows the dynamic behaviour of an atomic EDSDEVS model am_{EDS}. At time t_u the confluent transition function δ_{con} handles two concurrent events. The first event contains a bag covering external inputs received by the atomic model am_{EDS}. The figure

depicts an example bag covering three external inputs received at two different input ports. A concurrent internal event at t_u was scheduled by the previous execution of the time advance function *ta*. Depending on the specific implementation of function δ_{con} sequence a) or sequence b) is executed. The execution of the output function λ creates a bag covering outputs. The depicted example bag Y_u^b covers two outputs at two different output ports.

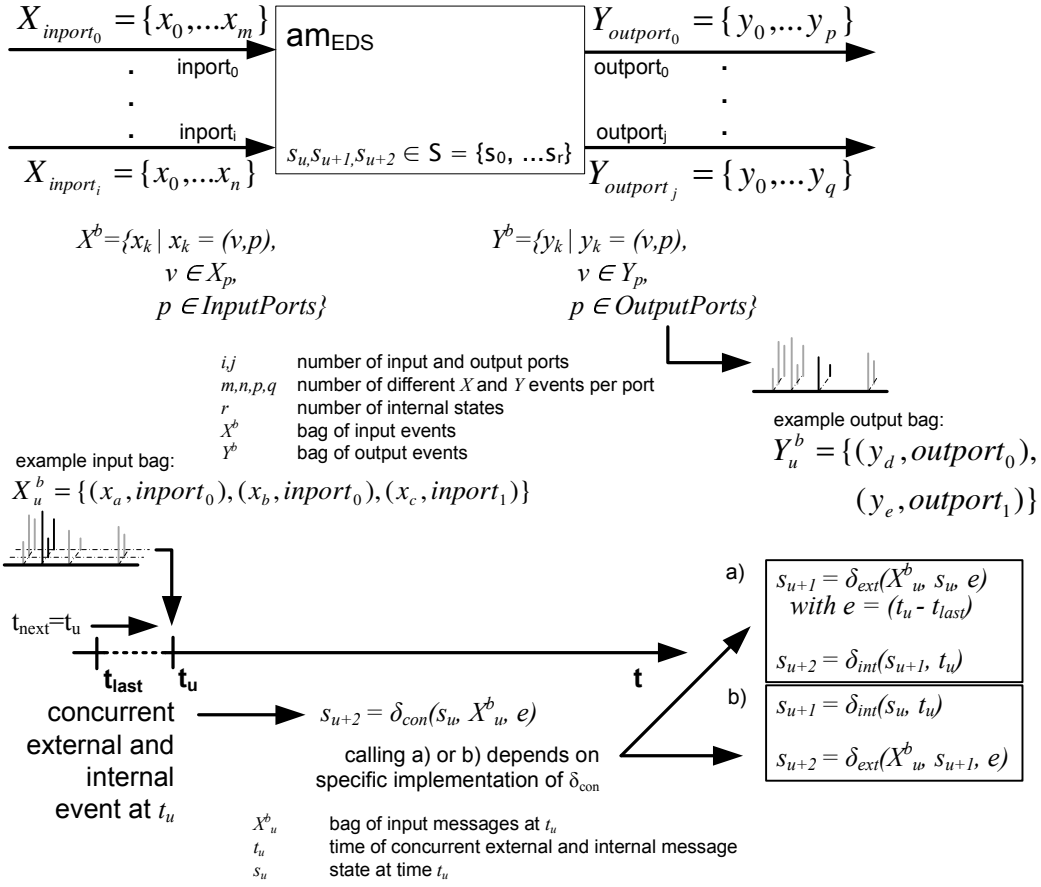


Figure 3.13 Dynamic behaviour of an atomic EDSDEVS model

Listings B.11 in appendix B shows pseudo code of an atomic EDSDEVS model.

A coupled EDSDEVS model is defined by the following 7-tuple:

$$CM_{EDS} = (d_{EDS}, S_{EDS}, \delta_{x\&s}, \delta_{int}, \delta_{con}, \lambda, ta)$$

- d_{EDS} specifies the name of the coupled model.
- In the EDSDEVS formalism the coupled model structure consists not only of sets of sub components and coupling relations as in DSDEVS, introduced in section 3.3.3,

but also of additional interface definitions i.e. input and output port definitions. The set of sequential structure states $\{s_0, s_1, ..., s_n\} = S_{EDS}$ has to define all structure variants of the coupled model CM_{EDS}. Two model structure variants can vary in different interface definitions, in contrast to DSDEVS where each model has a non-variable interface with a single input and a single output port. Hence, a structure state has to incorporate interface definitions with sets of input and output ports additionally to the structure state definition as introduced in section 3.3.3. An EDSDEVS structure state is defined by a 10-tuple:

$s_i = (X, Y, H_{EDS}, D, \{ M_d \}, InputPorts, OutputPorts, EIC, EOC, IC)$

- X and Y specify the sets of discrete input and outputs. The sets exactly match the extended definitions of X and Y as introduced in section 3.3.1 with the introduction of DEVS with Ports.
- The sets H_{EDS}, D and M_d exactly match the sets H_{DS}, D and M_d of the DSDEVS formalism introduced in section 3.3.3.
- *InputPorts* and *OutputPorts* specify the sets of input and output port names of the coupled model CM_{EDS}. These two elements of the structure state s_i are introduced by the EDSDEVS formalism.
- *EIC*, *EOC* and *IC* are the external input, external output and internal couplings of CM_{EDS}. The definition of the coupling relations exactly match the definition as introduced with the DEVS with Ports extension in section 3.3.1.

- $\delta_{x\&s}$: $Q \times X^b \rightarrow H_{EDS}$ where X^b is a bag covering input, input port pairs and

  $Q = \{(h,e) \mid h \in H_{EDS}, 0<e<t_{next}, \text{elapsed time } e = t - t_{last} \}$

  The external and state transition function δ_{ext} handles a bag covering inputs. Each input consists of a pair of:

- a discrete input $v \in X_p$ and an input port $p \in InputPorts$. The set X_P is the set of discrete inputs at port p and $InputPorts$ is the set of input ports of model CM_{EDS}.
- a discrete output $v \in M_d.Y_p$ and an output port $p \in M_d.OutputPorts$ where M_d is the model of the sub component d of the coupled model CM_{EDS}. The set $M_d.Y_P$ is the set of discrete outputs at port p and $M_d.OutputPorts$ is the set of output ports of model M_d.
- a discrete input $v \in M_d.X_p$ and an input port $p \in M_d.InputPorts$ where M_d is the model of the sub component d of the coupled model CM_{EDS}. The set $M_d.X_P$ is the set of discrete inputs at port p and $M_d.InputPorts$ is the set of input ports of model M_d.

This extended definition of δ_{ext} is a fusion and extension of the δ_{ext} definitions of DSDEVS, PDEVS and DEVS with Ports. In DSDEVS only state events induced by output events of sub components are handled. However, an output port can have coupling relations to multiple input ports. In this case there is a difference in the handling of a single output event of a single source sub model or multiple input events of different destination sub models. Hence, the external and state transition function of EDSDEVS can handle both output and input events. However, the functionality is in accordance with the description of the DSDEVS external and state transition function $\delta_{x\&s}$ introduced in section 3.3.3.

- δ_{int}: $S_{EDS} \rightarrow S_{EDS}$

  ta: $S_N \rightarrow \Re_0^+ \cup \infty$

  The internal state transition function δ_{int}, and the time advance function ta exactly match the functions of the DSDEVS formalism introduced in section 3.3.3.

- δ_{con}: $S_{EDS} \times X^b \rightarrow S_{EDS}$

The confluent transition function δ_{con} handles the execution sequence of δ_{int} and δ_{ext} functions during concurrent external and internal events.

The EDSDEVS formalism introduces the confluent transition function also at coupled model level due to the fusion of PDEVS and DSDEVS. A coupled EDSDEVS model handles external, state and internal events itself instead of only forwarding them as in PDEVS. Hence and in contrast to PDEVS, in EDSDEVS concurrent external and internal events can occur also at coupled model level. Consequently, a confluent transition function to handle concurrent events is also necessary at this level. The functionality is in accordance with the description of the confluent transition function δ_{con} for atomic model in this section.

- $\lambda: S_{EDS} \rightarrow Y^b$

  The output function λ can generate a bag covering outputs $Y^b = \{y_i\}$. An output y_i consists of a pair of discrete output $v \in Y_p$ and output port $p \in OutputPorts$. The set Y_P is the set of discrete outputs at port p and $OutputPorts$ is the set of output ports of model CM_{EDS}. If and which output event is generated depends on the internal state S_{EDS}.

  The output function λ in the EDSDEVS formalism merges three sources:

  - The output function λ at coupled model level is introduced by DSDEVS.
  - The definition of the function creating a bag covering outputs is based on PDEVS.
  - The output event structure with pairs of output/output port is introduced by DEVS with Ports.

The figure 3.14 shows the dynamic behaviour of a coupled EDSDEVS model CM_{EDS}. At time t_u the confluent transition function δ_{con} handles concurrent external and internal events. The first event is a bag covering inputs received at input ports by the coupled model CM_{EDS}. The figure depicts an example bag covering three external inputs received at two different input ports. A concurrent internal event at t_u was scheduled by the last execution of the time

advance function. Depending on the specific implementation of function δ_{con} sequence a) or sequence b) is executed. The execution of the internal state transition function δ_{int} can change the structure state s_u to s_{u+1} or s_{u+1} to s_{u+2} and therefore the model structure of CM_{EDS} to CM^*_{EDS}. The execution of the output function λ creates a bag covering outputs Y^b_u. The depicted example bag Y^b_u covers two outputs at two different output ports.

Listings B.12 in appendix B shows pseudo code of a coupled EDSDEVS model.

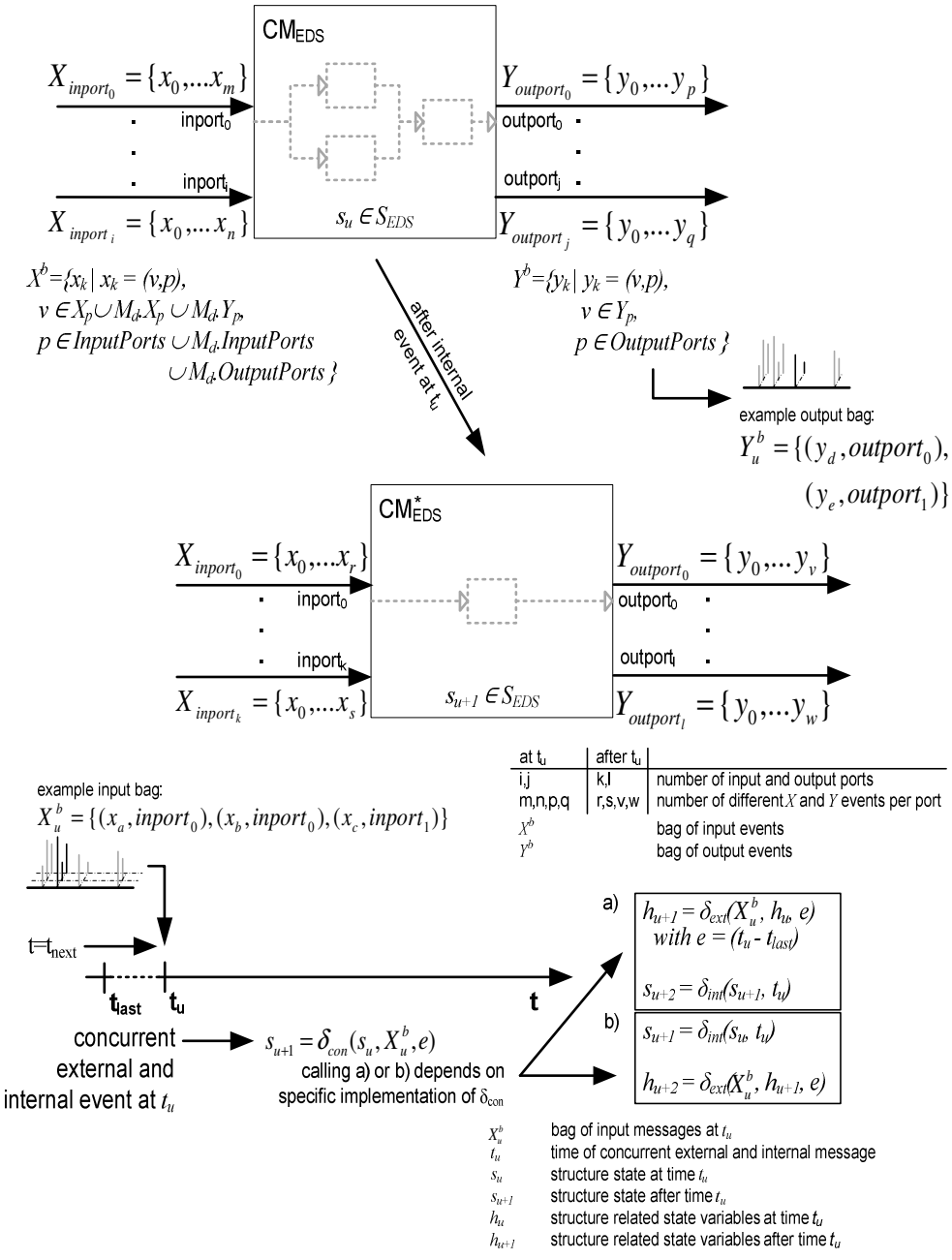


Figure 3.14 Dynamic behaviour of a coupled EDSDEVS model

3.4.2 EDSDEV Simulation

The simulation engine for EDSDEVS models is a combination and extension of the simulation algorithms of Classic DEVS, PDEVS and DSDEVS. The message handling of coordinators are largely similar to simulators. Each coordinator holds its own time of next internal event in t_{next_c} and searches the minimum time of next internal event in t_{next} of sub components and in its own t_{next_c}.

Figures 3.15 and 16 depict an EDSDEVS model example with the associated simulation model components i.e. root coordinator, coordinator and simulator instances and the message handling. The figure is based on and extends figure 3.7 depicting a Classic DEVS model example with associated simulation model components and message handling. The overall structure is very similar to the Classic DEVS simulation model execution except for additions at the levels of coordinator and associated coupled model. Because of complexity and clarity selected situations are shown in sections:

i. (Figure 3.15a) initialisation phase with i-message handling:

   During the initialisation phase model component's init functions are called because of an i-message handling similar to Classic DEVS. Additionally, after structure changes i.e. modification of the sub component set during the simulation phase the init function is called too.

ii. (Figure 3.16b) *-message handling created due to an internal event of model am2:

   The root coordinator advances the simulation clock and a *-message is firstly created. The message is sent to the successor coordinator instance of coupled model *CM1* (not depicted). This coordinator instance compares the actual simulation time *t* with its own next internal event time stored in t_{next_c} and determines that it is not responsible for handling this event. Hence, the event is forwarded to the successor coordinator instance of *CM2*. The coordinator instance is again not responsible for handling the message itself but knows that a sub component scheduled the event. The coordinator instance will then forward the message to the appropriate simulator

instance associated with *am2*. The simulator instance of *am2* calls the model functions λ and δ_{int}. A result of calling λ could be a y-message sent back to the subordinate coodinator instance of *CM2*. This coordinator instance reacts with the call of the model function $\delta_{x\&s}$ of *CM2* and a messge forward to the simulator instance of *am3* due to an appropriate IC coupling.

iii. (Figure 3.16c) *-message handling created due to an internal event of model CM2:

The depicted situation is similar to 3.16b except that the coordinator instance of *CM2* determines that simulation time *t* and its t_{next_c} are equal. Hence, it has to handle the *-message itself with calling λ and δ_{int} model functions of *CM2* with the possibility of generating a y-message sent to a sub component and/or superordinated coordinator instance and of changing its sequential structure state S_{EDS}.

iv. (Figure 3.16d) concurrent event handling with the confluent transition function δ_{con}:

The figure depicts the handling of concurrent external and internal messages by the coodinator instance of *CM2*. The confluent function of *CM2* is called to handle the concurrent messages. Depending on the specific implementation of δ_{con} the external transition function $\delta_{x\&s}$ and internal transition/output functions δ_{int}, respectively, are firstly called.The external message is concurrently handled by the function δ_{con} and forwarded to the simulator instance of sub component *am2* as a x-message due to an appropriate EIC. Calling the output function λ could cause a y-message sent to a sub component and/or superordinated coordinator instance.

v. (Figure 3.16e) x-message handling:

(i) x-message at $input_0$ of CM2 and due to an appropriate EIC at $input_0$ of am2:

The first x-message is received by the coordinator instance of *CM2*. This message is handled by the function $\delta_{x\&s}$ of the coupled model itself and concurrently forwarded to the simulator instance *am2* due to an appropriate EIC. Because no concurrent internal event exists the function δ_{con} is not called.

(ii) y-message at $output_0$ of am2 and due to an appropriate IC forwarded as x-message to $input_0$ of am3:

Due to an internal event the model *am2* generates a y-message. This y-message is handled by the super-ordinate coordinator instance which calls the function $\delta_{x\&s}$ of its associated model *CM2*. The coordinator instance concurrently forwards the y-message as an x-message to the simulator instance of *am3* because an IC exists between the output port $output_0$ of *am2* and the input port $input_0$ of *am3*.

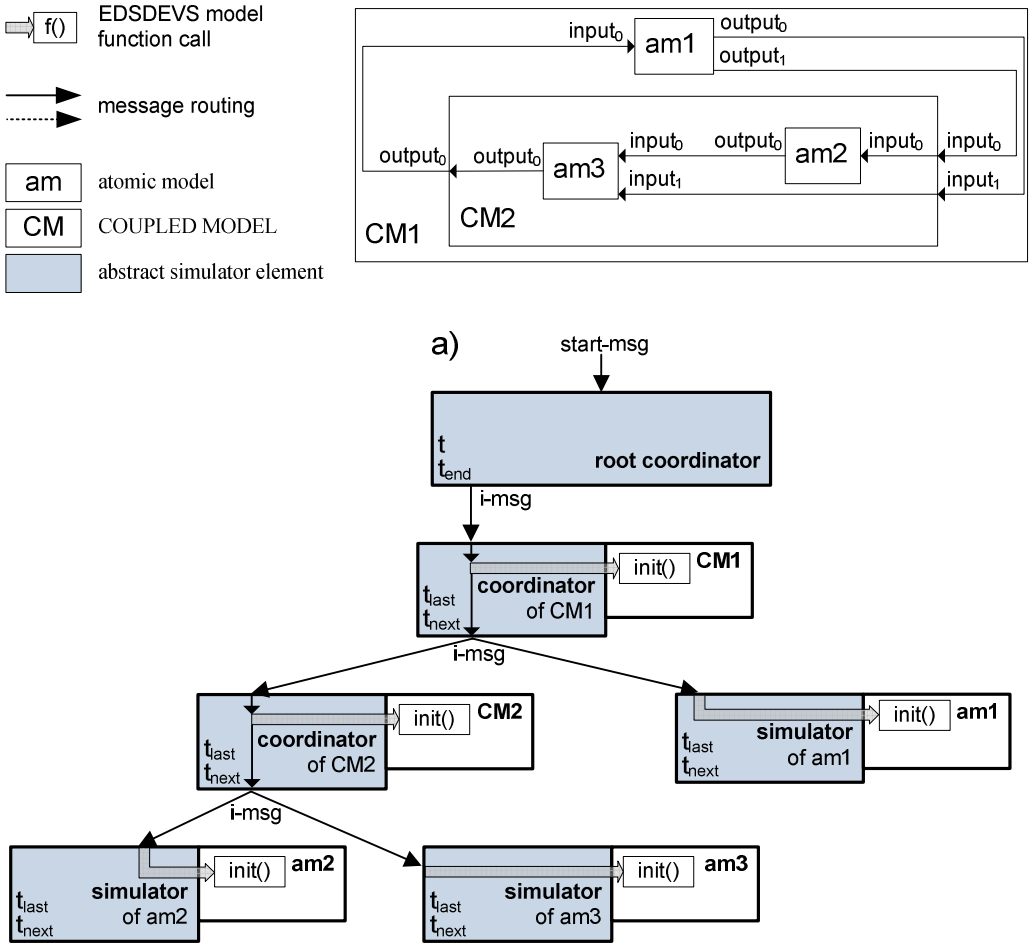


Figure 3.15 An EDSDEVS model example with associated abstract simulator elements, messages and model function calls during initialisation phase

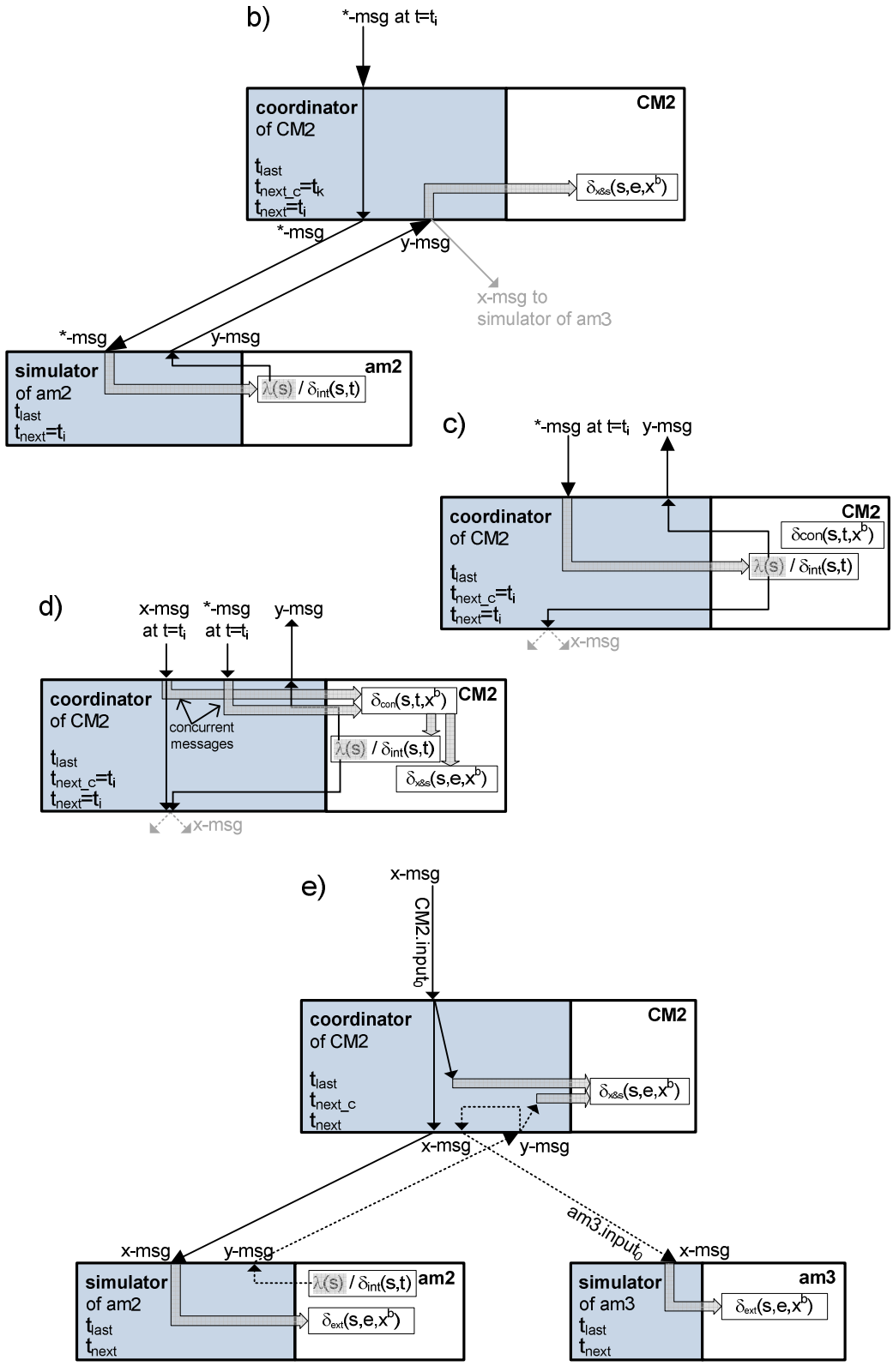


Figure 3.16 An EDSDEVS model example with associated abstract simulator elements, messages and model function calls during simulation phase

Listings B.13 and B.14 in appendix B show pseudo codes of EDSDEVS coordinator and simulator algorithms.

The EDSDEVS formalism developed from this research is a fusion of Classic DEVS with several extensions. It widens significantly the application area. This part of the research is an as generic as possible modelling and simulation formalism based on DEVS. Further extensions are desirable and essential. To establish a widely accepted modelling and simulation approach extensions for parallel computing and graphical modelling are necessary. There are also approaches for hybrid DEVS extensions i.e. the support of continuous state changes. These proposals are recommended as further research.

Chapter 4

Model Management – Model Set Specification and Organisation

Zeigler introduced in [66] a simulation based system design approach. It is a plan – generation – evaluation process. The *plan* phase organises design alternatives with different model structures and model parameters within defined system boundaries to satisfy given design objectives. During the *generation* phase a specific model design is chosen and the corresponding model is generated. This model is simulated during the *evaluation* phase using an experimental frame derived from the design objectives.

The System Entity Structure/Model Base framework (SES/MB) [52] [66] is such a simulation based system design approach. It is specifically configured to define, organise and generate modular, hierarchical models and was developed to assist an analyst in model organisation and generation. To represent a set of modular, hierarchical models, the SES/MB framework is able to describe three relationships: decomposition, taxonomy and coupling. *Decomposition* means the formalism is able to decompose a system object called 'entity' into sub-entities. *Taxonomy* means the ability to represent several possible variants of an entity called 'specialisation'. To interconnect sub-entities the definition of a *coupling* relationship is necessary.

The literature e.g. [52], [65] [66] and [69] describes slightly different specifications of the SES/MB framework. Hence, section 4.1 defines a classic SES/MB framework according to [52] and [66] as a basis for further extensions introduced in section 4.2.

4.1 Classic System Entity Structure/Model Base Framework

The SES/MB framework approach is [52] [66]:

- The framework consists of two parts: (i) the system entity structure and (ii) the model base.
- A modular, hierarchical model is constructed based on: (i) the declarative system knowledge coded in a SES and (ii) predefined basic system models stored in a MB.
- The partitioning of a modular, hierarchical model is highly dependent on the design objectives. Model parameters are a typical example. They are not really a part of the model composition structure but nevertheless they can become a part of the system entity structure if they are crucial for describing design alternatives.
- The model generation from a SES/MB is a multistage process. The first step is a graph analysing and pruning process to extract a specific system configuration. Based on this information a modular, hierarchical model is generated.

The SES is represented by a tree structure containing alternative edges starting at decision nodes. With the aid of different edge types and decision nodes a set of different model variants can be defined. To choose a specific design and to create a specific model variant the SES has to be pruned. The pruning process decides at decision nodes which alternative(s) to chose as a consequence of specified structure conditions and selection rules. The result of this process is a Pruned Entity Structure (PES) that defines one model variant. A composition tree is derived from a PES. The composition tree contains all the necessary information to generate a modular hierarchical model using predefined basic components from the model base (MB). Figure 4.1 shows the principal organisation and the transformation process: SES → PES → Composition Tree + MB → Modular, Hierarchical Model.

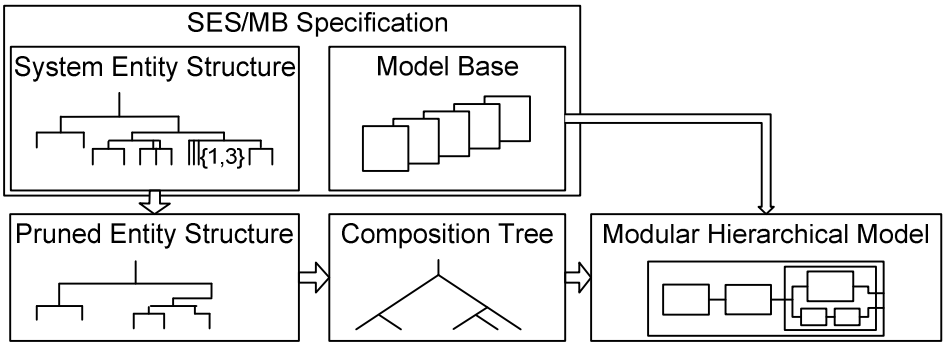


Figure 4.1 SES/MB formalism based model generation

The used SES definition is based on definitions published in [52] and [66]. A SES is a labelled tree consisting of different nodes with optional properties and different edge types. Figure 4.2 depicts a SES example which is referenced by the definition.

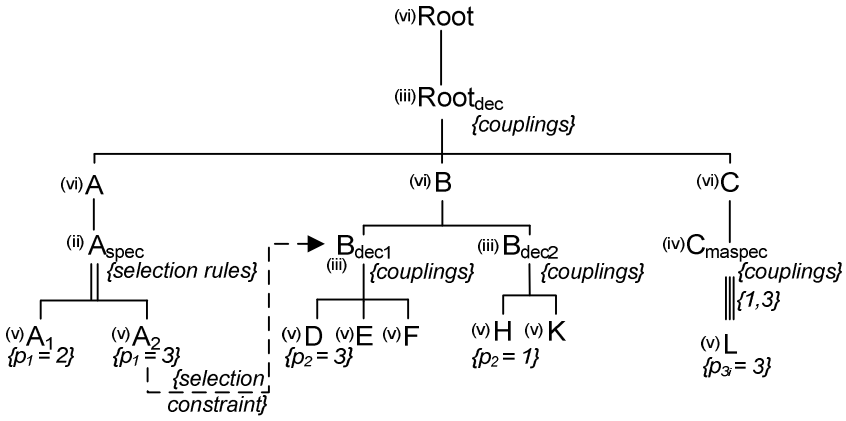


Figure 4.2 A SES example

The SES formalism differentiates four types of nodes: *(i) entity, (ii) specialisation, (iii) aspect* and *(iv) multi-aspect*. An entity node represents a system object. There are two subtypes of entity nodes – *(v) atomic entity* and *(vi) composite entity*. An *atomic entity* (figure 4.2 *(v)*) cannot be broken down into sub-entities. The model base contains a corresponding model for each *atomic entity*. Atomic models (described in chapter 3) and *atomic entities* must not be mixed at this point i.e. an *atomic entity* can also correspond to a coupled model in the model base. A *composite entity* (figure 4.2 *(vi)*) is defined in terms of other entities, which can be of type *atomic* or *composite entity*. Thus, the root node of a tree is always of type *composite entity*, while all leaf nodes are always of type *atomic entity*. The root node and each *composite entity* node of the tree has at least one successor node of type -

specialisation (figure 4.2 *(ii)*), *aspect* (figure 4.2 *(iii)*) or *multiple-aspect* (figure 4.2 *(iv)*). That means there is an alternate mode between entity nodes and the other node types. The definition of the different node types can be briefly summarised as follows:

atomic entity node = (name, {av_1,… av_n},selection constraints}

composite entity node = (name, successors, {av_1,… av_n})

An entity node is defined by a name and is of type *atomic* or *composite*. Both node types may have attached variables *av*. A *composite entity node* can have a single successor node of type *specialisation* or *multi-aspect* or multiple successor nodes of type *aspect*. An *atomic entity node* can have attached *selection constraints* when it is a successor of a *specialisation node*.

specialisation node = (name, successors, selection rules)

A s*pecialisation node* is defined by a name and a set of successor nodes. In the tree it is indicated by a double-line edge. A s*pecialisation node* defines the taxonomy of a predecessor entity node and specifies how the entity can be categorised into specialised entities. A s*pecialisation node* always has successor nodes of type atomic entity to represent the possible specialisations. A s*pecialisation node* can define additional s*election rules* to control the way in which a specialised entity is selected during the pruning process. *Selection constraints* are added to successor entity nodes of a s*pecialisation node*. The s*pecialisation node A* in figure 4.2 has two specialisations defined by the nodes A_1 and A_2. During the pruning process one of these specialisations is chosen. Due to the s*election rule* at node A_2 it is mandatory to chose node B_{dec1} when node A_2 is chosen.

aspect node = (name, successors, coupling specification)

An *aspect node* is defined by a name, a set of successor nodes and coupling information. It is indicated by a single-line edge in a SES tree. An *aspect node* defines a single possible decomposition of its parent node and can have multiple successors of type atomic and/or

composite entity. The *coupling specification* is a set of couplings and describes how the sub-entities, represented by the successor nodes, have to be connected. Each coupling is defined by a 2-tuple. Each tuple consists of sub-entity source and destination information, e.g. (SourceEntity.outputport, DestinationEntity.inputport). The composite entity *B* in figure 4.2 has two decomposition variants defined by the *aspect nodes* B_{dec1} and B_{dec2}. During the pruning process one of the decomposition variants has to be chosen.

Using SES/MB to describe a DEVS model an *aspect node* defines the composition of a coupled model.

multiple aspect node = (name, successor, coupling specification, number range property)

The definition of a *multiple* a*spect node* is similar to an aspect node. However, it defines additionally a *number range property* and has only one successor node of type atomic entity. It is indicated by a triple-line edge in a SES tree. A *multiple* a*spect node* also defines a decomposition of a composite entity, but all sub-entities have to be of the same entity. Only the number of sub-entities is variable according to the attached *number range property*. The *multiple* a*spect node* C_{maspec} in figure 4.2 illustrates the decomposition of composite entity *C* that may be composed by one, two or three sub-entities *L*.

A *multiple aspect node* also defines the composition of a coupled model.

In figure 4.3 a SES/MB example points up the complete process of model generation from a SES/MB to a modular hierarchical model. The SES tree defines a coupled model *CM1* with two structure variants. The two variants are defined by the specialisation node *CM2_spec* and specialisations *CM2.1* and *CM2.2*. The model base contains several basic components which are referenced by the SES. The different possible pruning results are PES *variant1* and *variant2*. After a transformation to a composition tree and a model generation, with the basic components taken from the model base, the final results are the modular hierarchical model *variant1* and *variant2*, respectively. The SES tree does not define selection rules or selection

constraints. Hence, an analyst has to use other, external criteria to decide which alternative structure should be chosen during the pruning process.

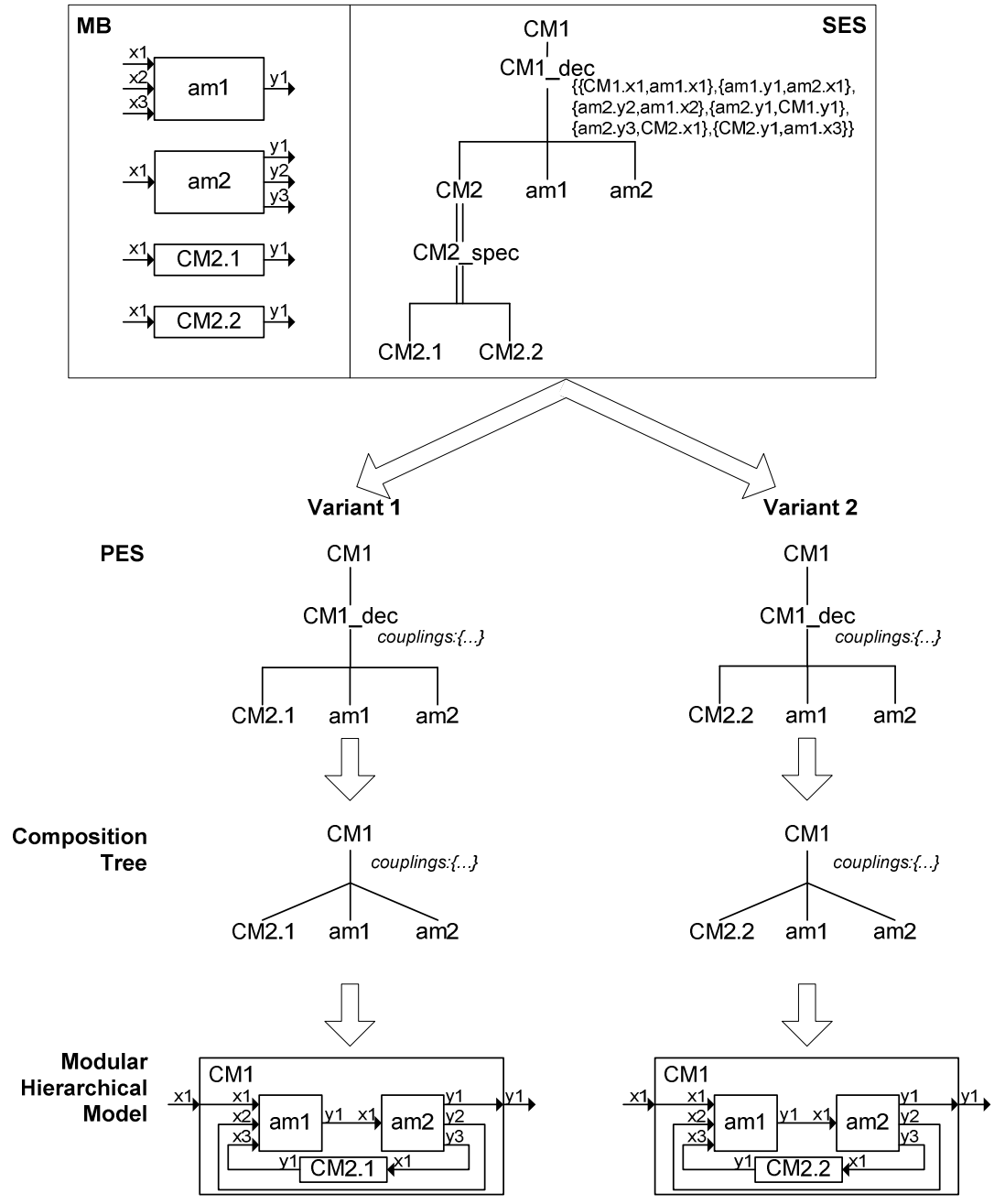


Figure 4.3 Detailed pruning and model generation example

4.2 Extension of the System Entity Structure/Model Base Framework

Originally the SES/MB framework was developed to assist an analyst during the model variant selection and a subsequent model generation. Pruning as a part of these processes is a

stepwise procedure with decisions at decision nodes under the control of selection rules and structure constraints. Both rules and constraints represent supplementary structure-knowledge as an addition to the structure-knowledge coded in the SES tree. The supplementary structure-knowledge is used to support the selection of design alternatives and to avoid invalid structures. This knowledge representation is customised to its usage during the pruning. The upper part of figure 4.4 depicts the steps of the original pruning process. An analyst initialises attached variables and makes decisions as long as unpruned decision nodes exist. A decision at a specific decision node can cause the pruning at other nodes according selection rules and structure constraints. The pruning in classic SES is a n-step procedure (n is equal or less than the number of decision nodes) with the goal to synthesise one valid model configuration.

In this research a new pruning principle is introduced. The lower part of figure 4.4 depicts the steps of the new pruning process. The new process is based on information delivered by the optimisation method as depicted in figure 2.5 and is carried out in a single step. A structure validation based on structure-knowledge is carried out after the pruning - not during - as in the original SES/MB framework. This important development means that the new pruning procedure requires another representation for structure-knowledge originally coded in selection rules and structure constraints. The new pruning of a SES tree is carried out in one step based on the structure parameter set X_{Si}. The model structure is verified in a second, following step. The new pruning algorithm is a 2-step procedure. Figure 4.4 identifies the differences between the original and new principle. A detailed description of the new approach is given in chapter 5.

Structure conditions as a new, alternative structure-knowledge representation are added to composite entity nodes. They are used as the alternative to selection rules and structure constraints as defined in [52] and [66]. During the pruning sub trees are removed. The remaining s*tructure conditions* are evaluated to verify the PES. Only if all *structure conditions* are true the PES is valid.

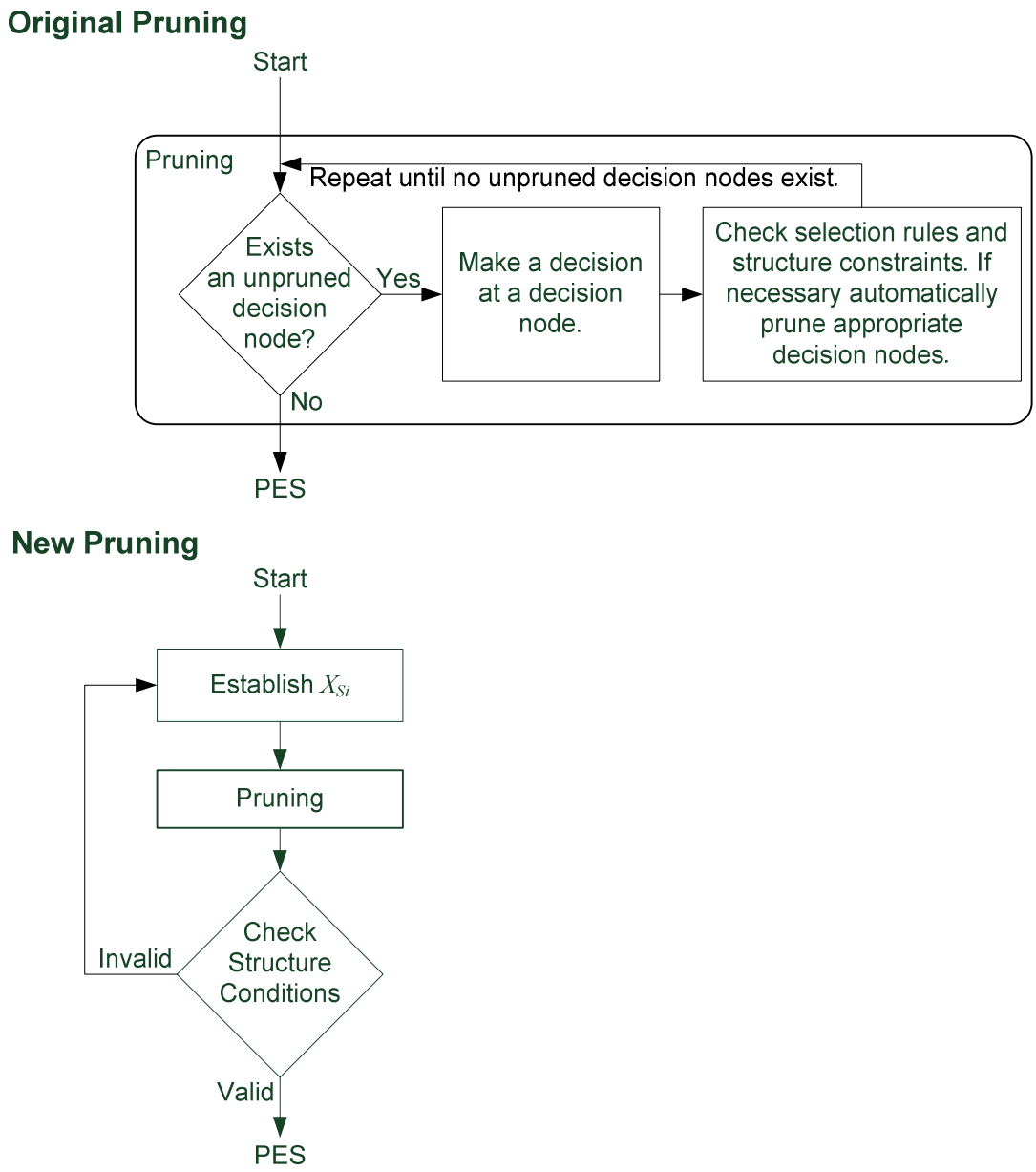


Figure 4.4 Comparison original pruning – new pruning principle

Figure 4.5 shows an example SES with a *structure condition* added to the composite entity node *ROOT*. The SES defines 12 different design variants whereas not all variants are valid according the *structure condition*. The figure depicts two variants, one valid and one invalid. If the generated model structure contains the atomic entity nodes *A2, D, E, F, L*, it would be valid because the *structure condition* $p_1+p_2+1*p_3=3+3+1*3<12$ is true. The second model structure variant contains the atomic entity nodes *A2, D, E, F, L, L*. It is not valid because the *structure condition* $p_1+p_2+2*p_3=3+3+2*3<12$ is false.

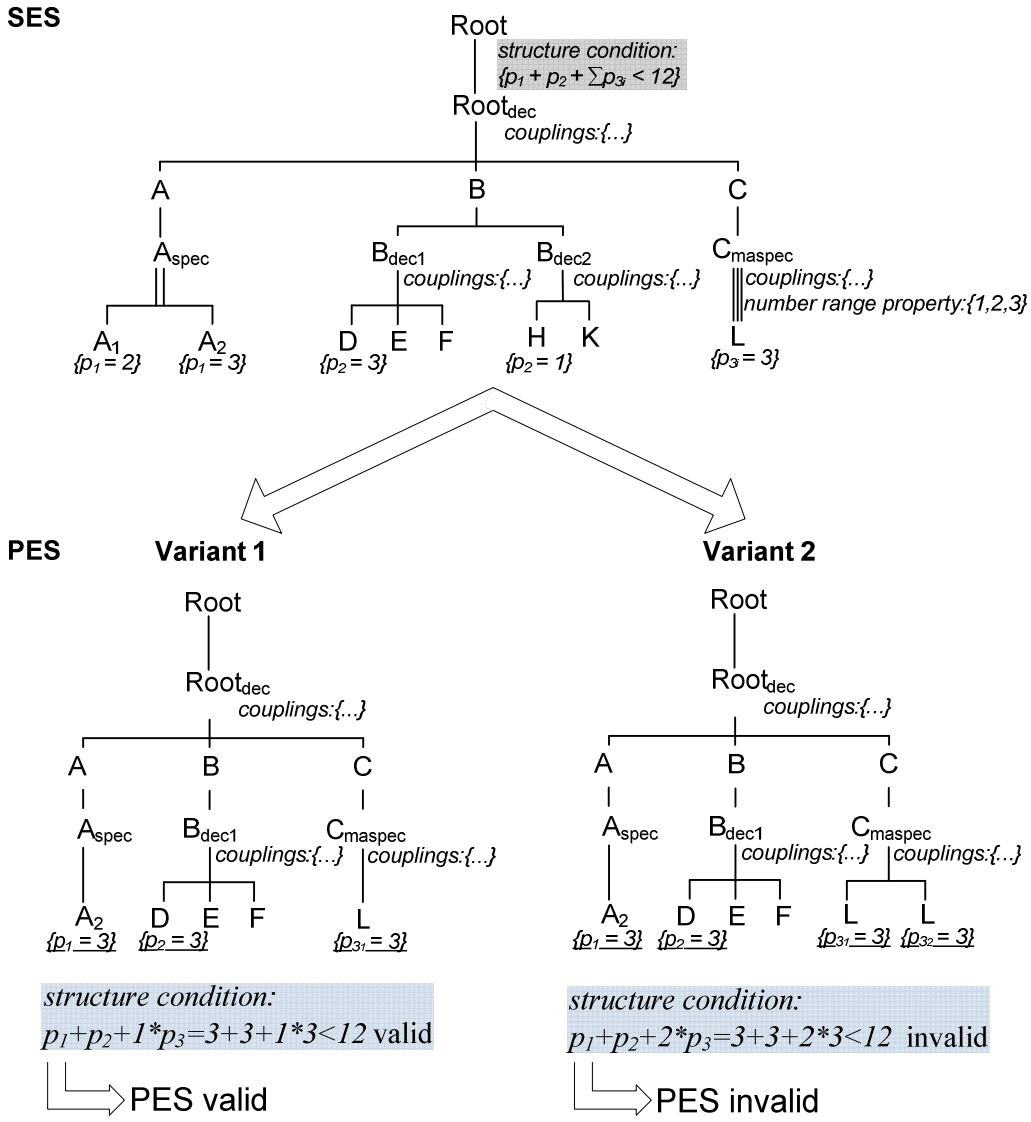


Figure 4.5 SES example with a structure condition

Chapter 5 provides the description of the application of the extended SES/MB framework. The chapter describes the combination of the introduced EDSDEVS formalism and SES/MB approach with an optimisation method to the simulation based parameter and structure optimisation as introduced in principle in section 2.3. The descriptions of the pruning and the terminal model generation processes, as a part of the SES/MB framework description, are provided in the context of other algorithms in chapter 5.

Chapter 5

A Framework for Modelling, Simulation and Optimisation

Chapter 2 introduced the key research concept - simulation based parameter and structure optimisation as a merging framework of three methods, optimisation, model management, and modelling and simulation. Chapter 3 introduced EDSDEVS as a modular, hierarchical modelling and flexible simulation formalism as applied in the framework, and chapter 4 defines the SES/MB approach as a suitable model management framework. In this chapter a complete framework for combined parameter and structure optimisation experiments is proposed. After a brief description of the general framework structure, its methods are discussed in detail and the entire algorithm is summarised. Finally implementation details to describe a SES/MB structure with XML are introduced.

5.1 General Framework Structure

A fundamental overview of a simulation based parameter and structure optimisation experiment is shown in figure 2.5. A more detailed structure of the framework with concrete elements and information flow is depicted in figure 5.1. The interface definitions between the three modules are a fundamental part of this approach. They bind the named methods together to synthesise a simulation based parameter and structure optimisation.

On closer examination of the framework it is crucial to divide an optimisation experiment into two phases:

1. Initialisation phase

   The model management reads and analyses a meta-model. Results of the analysis are information about the multidimensional search space (X_S, X_P, D_S ,D_P). The optimisation module is initialised with this information.

2. Optimisation phase

   During the optimisation phase the optimisation method explores the search space within a loop. Each examined search space point i.e. an ordered set of values (X_{S_i}, X_{P_i}) is delivered to the model management module. This module starts up the processes: structure synthesis, model generation, model simulation and performance estimation. The optimisation loop ends when a stop criterion is fulfilled. Examples of stop criteria are (i) going below a minimum alteration rate or (ii) exceeding the maximum number of optimisation cycles. The result of a successful finished optimisation phase is a parameter and structure optimised model.

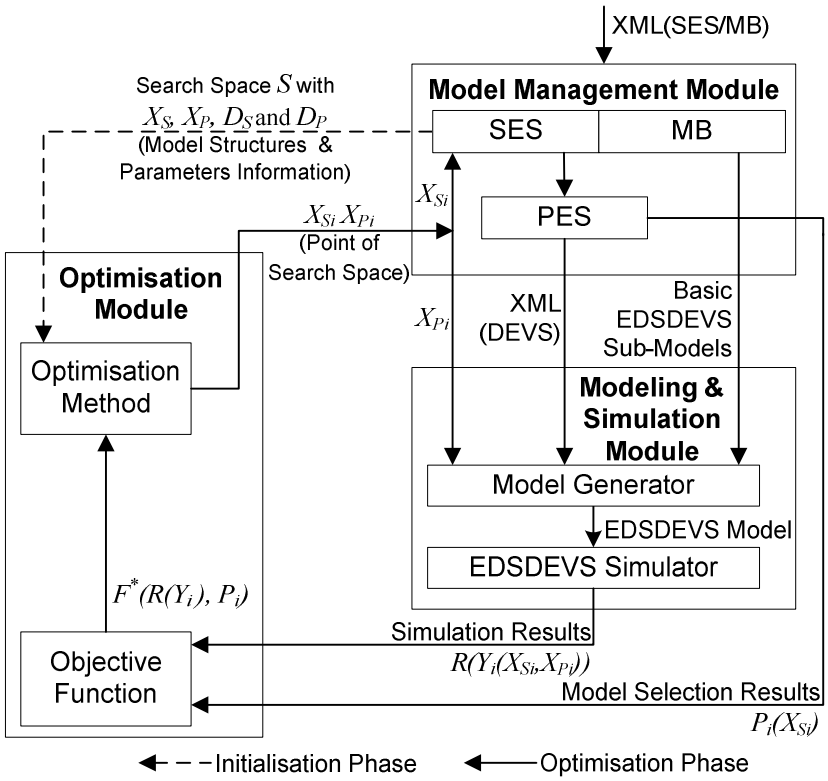


Figure 5.1 Structure of the simulation based optimisation framework

The simulation based optimisation framework is segmented into the following modules, methods and interfaces as depicted in figure 5.1:

1. Model Management Module: meta-model specification

   A meta-model definition is read and interpreted by the model management during the initialisation phase. A meta-model is defined in the form of a platform and implementation independent XML file. The basic components of a MB are regular EDSDEVS model components. They are referenced by the XML file with a model name and a model instance name. The result of this step is a data structure with an SES tree and references to a MB.

2. Interface Model Management Module – Optimisation Module: meta-model analysis

   In a second step during the initialisation phase the model management module analyses the SES tree and establishes the search space. The search space is defined by a set of variables with their domains. These sets X_S, D_S, X_P and D_P are sent to the optimisation module.

3. Interface Optimisation Module – Model Management Module: transformation of a search space points into a model configuration

   The model management module receives a search space point (X_{Si} X_{Pi}) within the optimisation loop. The sets X_{Si} and X_{Pi} are used to prune the SES, to synthesise the model structure and to parameterise the model. The selected model structure and model parameters are sent to a model generator as a platform and implementation independent XML files.

4. Model Generation Method

   Based on the received XML file with model structure information and references to basic components the model generator creates an EDSDEVS model.

5. Simulation Method

The EDSDEVS model is executed by an EDSDEVS simulator. In this research the modelling and simulation method is based on the EDSDEVS formalism. Principally this approach is not limited to EDSDEVS or DEVS formalisms exclusively.

6. Interface Model Management and Simulator – Objective Function

   In this approach the objective function gets both simulation results from the simulator and model structure selection results from the model management module to establish the performance of the current model structure and parameter set.

7. Optimisation Method

   The optimisation method establishes the next search space points to examine in a loop until the stop criterion is fulfilled. The search space points are chosen based on the search space definition and on previous objective function results.

5.2 Interface: Optimisation Module – Model Management Module

During the initialisation phase, the Model Management Module has to analyse the SES tree to transform formal meta-model structure information into numerical data useable by the Optimisation Module. Together with the model parameters the information is sent as initialisation data to the Optimisation Module. The information, coded in the four sets X_S, D_S, X_P and D_P is used to build the set $X^* = X_P \cup X_S$ and the corresponding domain set $D^* = D_P \cup D_S$. During the optimisation phase repeated in each optimisation loop cycle the optimisation method calculates a numerical data set $X_i^* = X_{Pi} \cup X_{Si}$. The set X_i^* is sent to the Model Management Module, which determines based on this information a new model configuration, i.e. a new model structure and initial model parameters. Both transformations are described by an example illustrated in figures 5.2 and 5.3.

The main task of the first transformation is to convert SES structure information to a structure parameter set X_S and the corresponding domain set D_S. This is done by a tree analysis starting at the root node, traversing the tree in a defined direction and considering every node. If a node is a decision node, i.e. it is a specialisation node, multiple aspect node

or composite entity node with alternative successor nodes, a structure parameter x_{Si} is added to the structure parameter set X_S and a corresponding domain d_{Si} to the domain set D_S. The domains of specialisation node and composite entity node are {1, ..., number of variants}. The domain of a multiple aspect node is defined by its attached number range property.

Two general principles can be applied to traverse the tree: (i) depth-first and (ii) breadth-first analysis. An advantage of the breadth-first analysis is the arrangement of the variables. If it can be assumed that variant decisions at a higher level of the SES tree have larger effects on the overall model structure than decisions near the leafs, a breadth-first analysis should be preferred. The breadth-first analysis sorts the elements of X_S and D_S as follows: elements on the left hand side of the ordered set correspond to higher levels of the SES; elements on the right hand side correspond to decision nodes nearer the leafs. An optimisation method could take this into account. Figure 5.2 illustrates the algorithm for creating structure parameter set X_S and the corresponding domain set D_S based on SES tree information. The analysis and X_S, D_S set build-up order is marked with small sequence numbers.

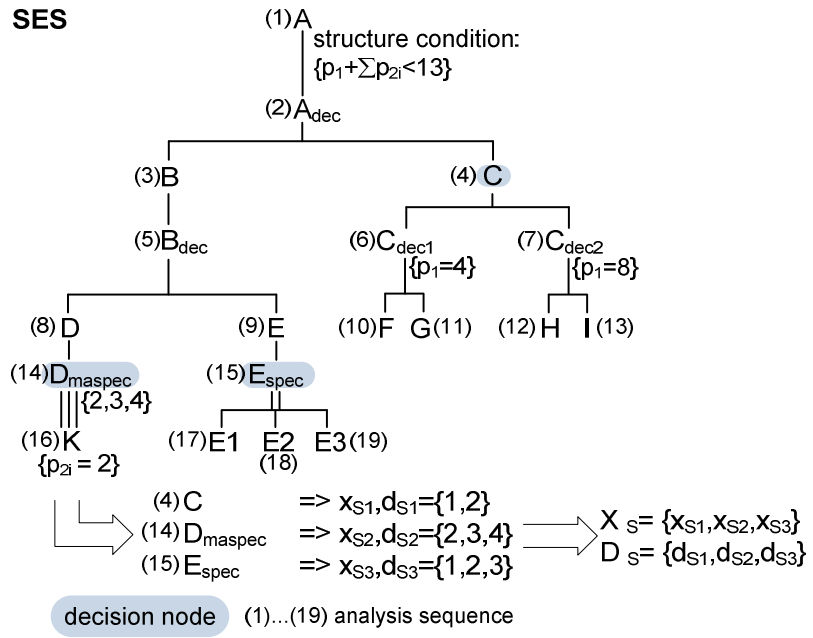


Figure 5.2 Transformation SES → set X_S and set D_S

The breadth-first analysis starts at the root node *A*, a non-decision node. Next nodes are non-decision nodes A_{dec} and *B*. The composite entity node *C* is the first decision node. It has two alternative successors. A first parameter x_{S1} is added to set X_S with the domain $d_{S1} = \{1, 2\}$. The next examined nodes are B_{dec}, C_{dec1}, C_{dec2}, *D*, *E*, *F*, *G*, *H* and *I* - they are non-decision nodes. The next examined node, the multiple aspect node D_{maspec} is a decision node. The value of its number range property is {2, 3, 4}. A second parameter x_{S2} is added to X_S with the domain $d_{S2} = \{2, 3, 4\}$. The next node, the specialisation node E_{spec} is again a decision node. It has three alternative successor nodes. A third parameter x_{S3} is added to X_S with the domain $d_{S3} = \{1, 2, 3\}$. The last nodes analysed *K*, E_1, E_2 and E_3 are non-decision nodes. The example SES has three decision nodes. The resulting structure parameter set is $X_S = \{x_{S1}, x_{S2}, x_{S3}\}$ with the corresponding domain set $D_S = \{d_{S1}, d_{S2}, d_{S3}\}$ with the above determined domains. On the basis of the combination of these sets X_S, D_S, the model parameter set X_P and its corresponding domain set D_P the optimisation method is able to search the search space. Additional SES tree information e.g. the structure condition at node *A* and the attached variables p_1 and p_2 in figure 5.2 are irrelevant during the initialisation phase.

The second transformation is the reverse of the first. The Model Management Module receives a point in the search space from the Optimisation Module i.e. the numerical data set $X_i^* = X_{Pi} \cup X_{Si}$, where set X_{Si} codes a specific model structure and set X_{Pi} codes its model parameters. It has to synthesise the corresponding model structure and has to infer the model parameters. The transformation has to traverse the tree in the same direction as during the first in the initialisation phase. At each decision node the next element of current structure parameter set X_{Si} is used to decide: (i) which successor of a composite entity node with alternative successors nodes is chosen, (ii) which specialisation of a specialisation node is chosen or (iii) how many successors of a multiple aspect node are incorporated into the PES. After pruning the model structure is verified with the evaluation of all structure conditions. If a structure is invalid the specific set X_i^* will be refused and this information is

sent to the Optimisation Module. It marks this point in the search space as prohibited and determines a new one. Figure 5.3 illustrates the principle of this transformation. The analysis and pruning order is marked again with small sequence numbers.

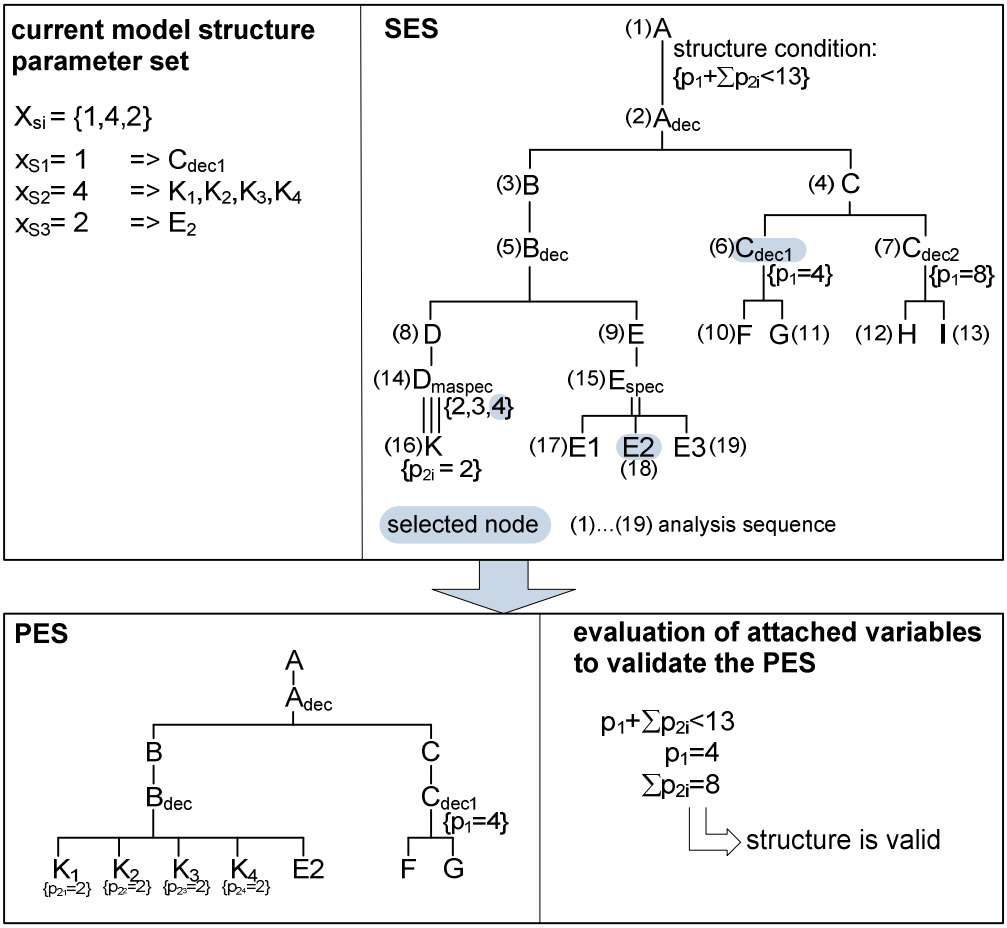


Figure 5.3 Transformation X_{Si} + SES → PES

The breadth-first analysis starts at the root node *A* and continues as already described before. The first decision node of the SES tree in figure 5.3 is composition entity node *C*. The first element in X_{Si} is $x_{S1}=1$, i.e. the first aspect node C_{dec1} is chosen for the PES. The next decision node is the multiple aspect node D_{maspec} and the corresponding set element is $x_{S2}=4$, i.e. the PES contains four nodes *K*. The last decision node is specialisation node E_{spec} and the corresponding set element is $x_{S3}=2$, i.e. the PES contains the second specialisation of node E_{spec}. After pruning, the attached variables are calculated and the PES is verified by evaluating the relevant structure conditions. In the example in figure 5.3, the aspect node C_{dec1} and four atomic entity nodes *K* were chosen. Therefore, the structure condition at node

A is evaluated as follows: $p_1 + \sum p_{2i} = 4 + 8 < 13$ and from this it follows that the PES is valid.

5.3 Interface: Model Management Module – Modelling and Simulation Module

Each optimisation cycle requires a change and adaptation of the simulation model. If the structure parameters in X_{Si} are changed, a new simulation model structure has to be generated. Otherwise, if just the model parameters in X_{Pi} are changed, it is adequate to re-initialise the model parameters. As illustrated in figure 5.1 all necessary information is sent from the Model Management Module to the Model Generator of the Modelling and Simulation Module. The Model Management Module creates XML files describing the model structure. EDSDEVS basic components, predefined in the MB, XML files and current model parameters coded in set X_{Pi} are used by the Model Generator to generate the entire EDSDEVS model.

The use of a standardised XML model description for information exchange decouples the two modules. It is based on W3C XML schema Finite Deterministic DEVS Models introduced in [30] and [31]. The XML interface uses the atomic and coupled model interface descriptions with model and port names. The coupled model description described in [31] is currently work in progress and does not contain all necessary description elements for this approach. Therefore, the composition description of coupled models additionally defines sub model names and coupling specification. The coupling specification defines external input (EIC), external output (EOC) and internal coupling information (IC). An example with corresponding XML files is illustrated in figure B.1 and listings B.17 and B.18 in appendix B.

The decoupling of Model Management Module and Modelling and Simulation Module using XML files eases the modelling and verification of the basic components

without the Model Management Module. Additionally it will enable and ease the use of different simulator implementations; however this will be the subject of future work.

5.4 Interface: Modelling and Simulation Module – Optimisation Module

The objective function, defined in the Optimisation Module, (figure 5.1), estimates the performance of the current model structure and parameter values. The function gets its input parameters from the Modelling and Simulation Module. These are the simulation results $Y_i(X_{Si}, X_{Pi})$ and simulation response function results $R(Y_i(X_{Si}, X_{Pi}))$ respectively. Further input parameters are delivered by the Model Management Module. These are the model structure results $P_i(X_{Si})$, which are based on evaluation of attached variables after pruning the SES. An example is illustrated in figure 5.2. The aspect nodes C_{dec1} and C_{dec2} and the atomic entity node K define the attached variables p_1 and p_{2i}. After the pruning process illustrated in figure 5.3 the values of p_1 and p_2 are calculated as follows: $P_i(X_{Si}) = \{p_1; \sum p_{2i}\} = \{4;8\}$. These values may be used as further objective function parameters.

The result $F^*(R(Y_i), P_i)$ of the objective function is evaluated by the optimisation method. As a consequence of the often stochastic nature of simulation problems, a random based optimisation method is preferable. Two established random based algorithms inspired by the principle of the evolution of life are the Genetic Algorithm (GA) introduced by Holland [20] and the Evolutionary Strategy (ES) introduced by Rechenberg [50]. The origins of ES are continuous parameter problems whereas current GAs support hybrid problems. There is an extensive and varied body of literature on this topic. Genetic algorithms have delivered robust solutions for various simulation based optimisation problems e.g. in [47] and [49]. Experiments realised within the scope of this research have shown that a GA is applicable as an optimisation method for the simulation based optimisation approach.

The methods of the simulation based parameter and structure optimisation framework described in this chapter are integrated into a general GA algorithm (listing B.19

in appendix B). The resulting algorithmic summary of the whole framework is introduced in the next section.

5.5 Algorithmic Summary of the Framework

As described in the preceding sections, the proposed simulation based parameter and structure optimisation framework is composed of different methods that form a uniform optimisation approach. The following algorithm, based on the general description in [54], summarises the fundamental operations using a GA as optimisation method.

Initialisation Phase:

0. Analyse the SES and establish $X^* = X_P \cup X_S$ and $D^* = D_P \cup D_S$
1. Initialise a population of individuals (generation 0) with different $X_i^* = X_{Pi} \cup X_{Si}$

Optimisation Phase (repeat until stop criterion is fulfilled):

2. Estimate the fitness of all individuals of the current generation

   Repeat for each individual

   2.1. Prune SES with X_{Si}

   2.2. If structure condition is valid, establish $P_i(X_{Si})$ or otherwise mark current individual as invalid and continue with next individual

   2.3. Generate EDSDEVS model

   2.4. Simulate EDSDEVS model and get result $Y_i(X_{Si}, X_{Pi})$

   2.5. Evaluate the simulation response function $R(Y_i(X_{Si}, X_{Pi}))$ by repeating step 2.4

   2.6. Evaluate the objective function $F^*(R(Y_i), P_i)$
3. Select pairs with *m* individuals and create descendants using crossover
4. Mutate the descendants
5. Exchange individuals of the current generation with descendants based on a substitution schema to create a new generation

A disadvantage of a conventional GA is the missing memory. It is possible that in different generations the same individual is repeatedly examined. Because of the time consuming

fitness estimation of one individual in simulation based optimisation, the addition of a memory method is vitally important. It has to store already examined individuals with their resulting $F^*(R(Y_i), P_i)$. This extension leads to the following, final algorithm summarising the fundamental operations of the simulation based parameter and structure optimisation approach using a GA as optimisation method:

Initialisation Phase:

0. Analyse the SES and establish $X^* = X_P \cup X_S$ and $D^* = D_P \cup D_S$
1. Initialise a population of individuals (generation 0) with different $X_i^* = X_{P_i} \cup X_{S_i}$

Optimisation Phase (repeat until stop criterion is fulfilled):

2. Estimate the fitness of all individuals of the current generation

   Repeat for each individual

   2.1. Check memory if current individual is known. In case of 'true': continue with next individual

   2.2. Prune SES with X_{Si}

   2.3. If structure condition is valid, establish $P_i(X_{Si})$ or otherwise mark current individual as invalid and continue with next individual

   2.4. Generate EDSDEVS model

   2.5. Simulate EDSDEVS model and get result $Y_i(X_{Si}, X_{Pi})$

   2.6. Evaluate the simulation response function $R(Y_i(X_{Si}, X_{Pi}))$ by repeating step 2.5

   2.7. Evaluate the objective function $F^*(R(Y_i), P_i)$

   2.8. Store X_i^* and $F^*(R(Y_i), P_i)$ in memory
3. Select pairs with *m* individuals and create descendants using crossover
4. Mutate the descendants
5. Exchange individuals of the current generation with descendants based on a substitution schema to create a new generation

5.6 Definition of a Model Set with XML SES/MB

In chapter 4 the extended SES/MB framework for the simulation based optimisation framework was formally introduced. This section describes the meta-model definition with the framework in detail. In this approach an SES/MB meta-model definition is based on XML [64]. Therewith the definition is platform and implementation independent. The usage of XML has the potential to enable the development of further extensions e.g. a graphical model designer. Figure 5.4 depicts the UML 2.0 [61] class and composition structure diagram of the XML schema and listing B.15 in appendix B contains the document type description (DTD [64]). Both the schema and the DTD are describing the structure of an SES/MB XML file.

The structure is divided into three main sub structures (i) SES tree, (ii) MB, (iii) properties:

1. The SES tree sub structure is defined within the *ses* sub tree of the XML structure. The six nodes (i) *composite*, (ii) *atomic*, (iii) *multiaspect*, (iv) *aspect*, (v) *specialisation* and (vi) *specialisation-entity* correspond to the different entity types of the formal SES/MB description as introduced in chapter 4. An exception is the specialisation-entity node which matches an atomic node. It is introduced to eases the SES XML file verification. The connections within the UML class and composition diagram defines the container class/contained class relationship and the m:n relations between both components. Each component has one attribute, the entity name *esname*. This name is used to logically connect XML elements within the XML SES, MB and property sub structures e.g. an *atomic* entity definition from the *ses* sub tree with the *mb_atomic* model implementation definition from the *modelbase* sub tree.
2. The MB is defined within the *modelbase* sub structure. The sub structure references (a) model implementations and defines (b) model interfaces:
    a. Nodes of the type *mb_atomic* and *mb_specializationentity* references basic components. The models are not directly defined within an SES/MB XML

file. The above nodes refer to a model implementation. The attribute *classname* refers to the model implementation class name and the attribute *modelname* names the specific model instance name. Both class and instance names are necessary to enable multiple usage of a component. The node *mb_aspect* is not a reference to a model implementation but is used to synthesise a model during model generation.

b. Nodes of the type *atomic, specialization* and *aspect* have attached coupling information. Hence the corresponding *modelbase* nodes *mb_atomic, mb_aspect* and *mb_specialization* define interfaces with input and output ports. Each model i.e. the corresponding structure in the *modelbase* can have several *inport*s and *outport*s named with the attribute *name* and combined in list structures *inports* and *outports*. Even though a specialisation node does not have a model implementation it has a definition in the *modelbase* sub tree. All child nodes of a specialisation share the same interface description which is defined once at parent node level.

3. To avoid scattered node property definitions all properties are defined in the *properties* sub structure. An aspect node defines a coupled model i.e. besides the sub components defined within the *ses* sub structure additional coupling information are necessary. A *modelcouplings* sub structure with a corresponding name in the *esname* attribute describes the coupling information in *eic*, *eoc* and *ic* lists. The number of possible children of a multiple aspect node is defined by the *varNumberOfComponent* structure. Nodes can have attached variables defined within the *var* structure and coupled with the *esname* attribute to the corresponding *ses* sub structure. Optional structure conditions are defined within the *constraint* structure.

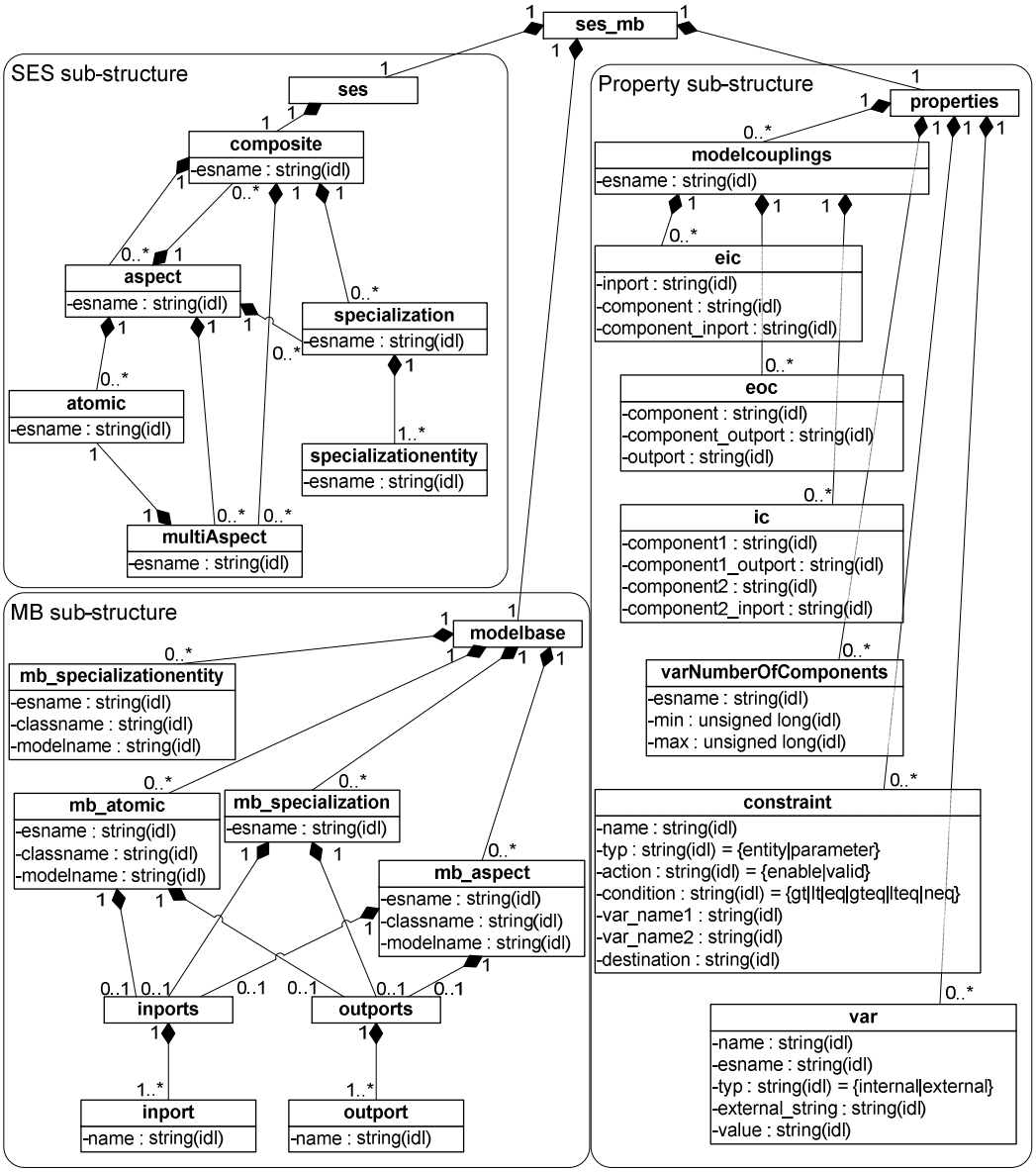


Figure 5.4 UML Diagram of SES/MB XML Schema

The example SES in figure 5.5 defines two structure variants through two different specialisations A_1 and A_2 at A_{spec}. With the structure condition at the *ROOT* entity the PES can be verified after pruning. Figure 5.5 depicts the structure variants after pruning and model generation. Due to the structure condition only one model variant is valid. The listing B.16 in appendix B shows the corresponding meta-model definition with an SES/MB XML file. The three sub structures *ses*, *modelbase* and *properties* are separated with an empty line, XML elements, attributes and values are highlighted with different colours.

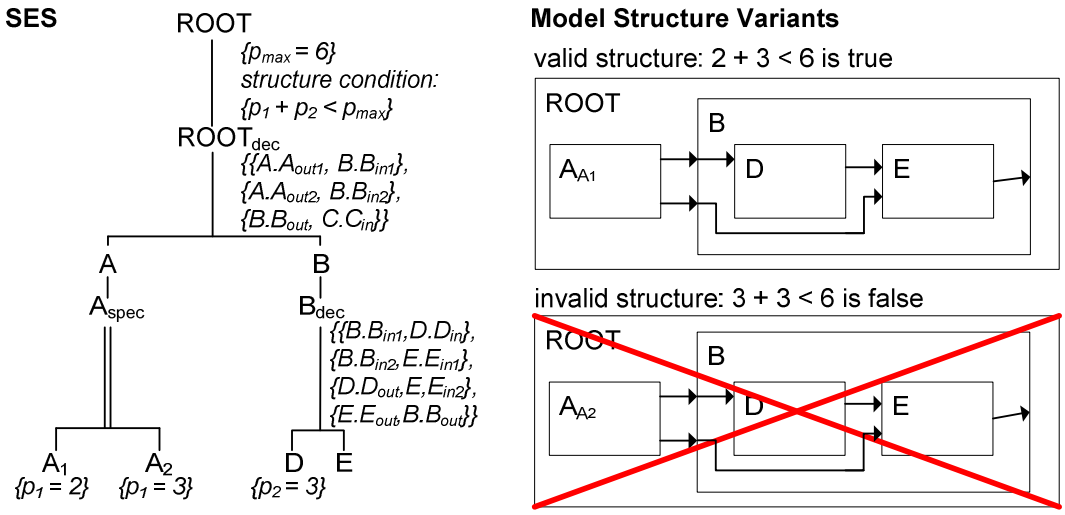


Figure 5.5 An SES/MB XML example – SES tree with both valid and invalid model structure variants

The next chapter starts with an overview of modelling and simulation of manufacturing systems and demonstrates the application of the introduced framework with a project from industry.

Chapter 6

Parameter and Structure Optimisation of Manufacturing Systems

This chapter demonstrates the application of the introduced framework for a simulation based parameter and structure optimisation with a real industrial project. It starts with a short review of types, components and complexity of manufacturing systems in the context of modelling and simulation. Current manufacturing system planning concepts and a range of modelling and simulation concepts for manufacturing system simulation are presented in an overview.

A broad choice of modelling and simulation packages is commercially available, developed to reflect the changing requirements of manufacturing applications. As discussed in chapter 2 not all demands of manufacturing modelling and simulation are satisfied optimally. A real life example using the approach developed in this research demonstrates how this can be accomplished.

6.1 Manufacturing Systems

The focus of manufacturing is the combination and transformation of raw material to a product with a market potential using industrial machines [21] [22]. This is a very simple principle but is difficult to achieve and maintain. The challenge is that the market potential and the requirements of manufacturing system are changing continuously. A manufacturer who does not adapt will lose competitiveness and vice versa a company that handles these

changes most effectively will succeed. A major issue for managers and engineers is the continuous analysis of manufacturing system performance and the use of methods to improve operations and adapt to new market situations. Analysis using modelling and simulation is potentially a powerful management method.

Depending on the point of view it is possible to differentiate between several types of manufacturing systems. Two widely used, described in more detail in [5] are the following:

- serial system

  An assembly line as a typical example of a *serial system* is a sequential set of workstations connected by material handling systems. Component parts are assembled or machined to produce a finished product in a line. The assembly activity can be divided into work elements as the smallest unit of productive work. A subset of work elements are assigned to each workstation. A work piece passes the complete line in a sequence. After leaving the final workstation the product is complete. Such systems are often used to produce a high volume of a small number of similar products. Figure 6.1 shows an example of a serial system with several lines with sub assembly manufacturing and a final end product assembly line.

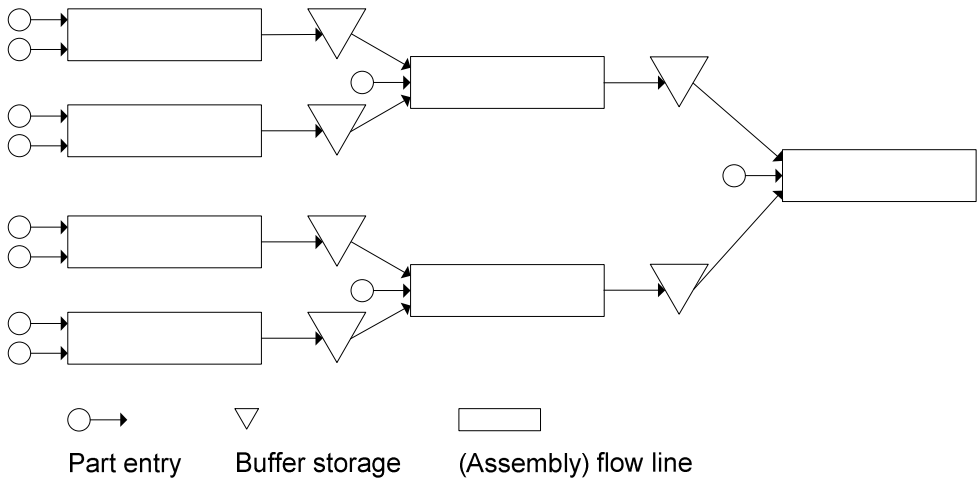


Figure 6.1 General assembly system layout (source [5])

- shop scheduling system

  In contrast to a serial system a *job scheduling system* manufactures a variety of different products. Work pieces can follow different routes with significant different processing time at a workstation. Regularly work pieces are combined in batches or jobs of one or more parts which are manufactured on the same route i.e. with the same production sequence and similar processing time. If all batches are processed in the same sequence of workstations the system is named *flow shop*. In contrast, in a *job shop* each batch type has the same production sequence. With a growing flexibility and pressure to decrease manufacturing cost the complexity of job shop systems is increasing considerably. Hence the planning of *job shop* systems is making greater than ever demands.

6.2 Modelling and Simulation of Manufacturing Systems

The simulation of manufacturing and material handling systems is one of the most important applications of discrete event modelling and simulation techniques [7]. These techniques have been successfully used as an aid in the design of new systems as well as an evaluation tool for improvements to existing systems, as a daily staffing, material and operation planning tool and so on.

Even though both the types of manufacturing systems and the analysis issues vary substantially the different modelling and simulation techniques share some common characteristics as described in the following sections.

6.2.1 Simulation Model Level of Detail

In principle every model is an approximation of the real world. Depending on the analysis objectives irrelevant characteristics and details can be omitted when creating a model. In simulation literature this principle is called *level of abstraction* [51] because the model is an abstraction or approximation of the real system. The appropriate level of detail can

distinguish between valid and invalid or successful and unsuccessful simulation experiments. It is claimed that a good rule is to add details step by step during a model validation process because starting with a low level of detail usually leads to fewer simulation results to be validated [51]. The analyst stops the process when the model is close enough to real system behaviour to provide results for analysis. This validation approach is an iterative process that results in a sufficiently accurate model. Figure 6.2 depicts the correlation between model detail and validation time [51]. The asymptotic behaviour of the relationship may mean more effort to increase the level of detail from 95% to 100% than creation of the initial model with 95% accuracy.

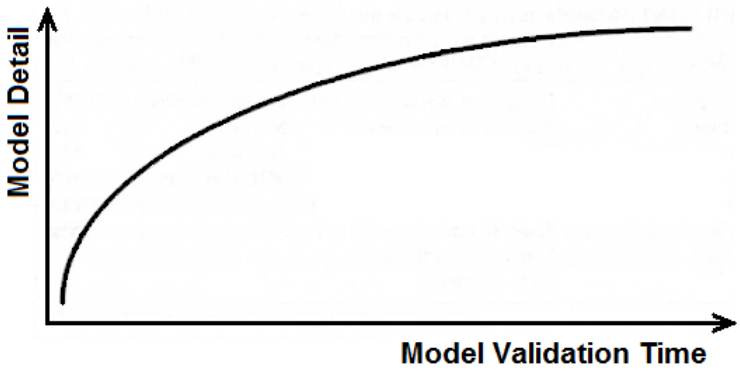


Figure 6.2 Model detail during model validation (source [51])

6.2.2 Fundamental Components

Manufacturing systems produce a wide range of products with many types of production methods using many different system layouts. Nevertheless there are common components that can describe many manufacturing operations. These common components are the basis elements of a simulation model [51]. Table 6.1 depicts these basic elements.

Product	Resource	Demand	Control
Parts/pieces	Equipment layout	Customer orders	Warehouse management
Routings	Equipment costs	Start date	Inventory control
Process time	Number of machines	Due date	Shop floor control
Setup time	Failure	WIP inventory	WIP tracking
Bill of material	Maintenance		Restricted resources
Yield	Number of operators		Station rules
Rework	Shift schedules		

Table 6.1 Fundamental components of manufacturing systems (source [51])

Product. *Parts or pieces* are the products manufactured. Products may be handled as a single item or production unit or combined to batches depending on the manufacturing process named batch or job. A batch can be described as a production unit in a subsequent process. Products are manufactured in a defined sequence, the *routings*. Depending on the manufacturing process and on the product the *routing* can be sequential e.g. in an automobile assembly line i.e. a serial system or complex e.g. in a semiconductor production process i.e. a job scheduling system. For each manufacturing step the *setup and processing time* determine the total cycle time. These times depend on the machine and/or product and can be deterministic or stochastic.

A product can be assembled from several items, i.e. sub assemblies, defined by the product structure file or *bill of material (BoM)*. Each item in the BoM can be the result of a production process. During the manufacturing process all BoM items must be available at a defined point of time relative to the final product assembly or product due date. The modelling of manufacturing systems with a delivery or production of sub assemblies Just-In-Time to minimise waste and inventory is an important manufacturing paradigm today. The typical example of this principle is the automobile industry.

Yield and *rework* are found in many manufacturing processes. The reasons are imperfect processes and operations. Both factors influence the process throughput and other

characteristics e.g. the costs. With a lower level of detail both characteristics can also be omitted.

Resources. Resources include machines and human operators, mobile and immobile equipment, material and storage systems etc. They are used to manufacture a product. The *equipment layout* and the *number of machines* have an effect on the production flow and the speed of operation. The *equipment costs* influence amongst others the manufacturing cost of a product. Staff number can be a restricted resource, e.g. the number of machines and with these the necessary *number of operators* is higher than the available number of operators. In this context *shift schedules* have to be possibly considered.

The equipment has unplanned and planned down times, random *failures* or regular *maintenance*. During these times production has to stop or product flow has to be rerouted when alternatives are available.

Demand. *Costumer orders* define the demands on a manufacturing process. *Start and due dates* are determined by these customer orders for products. An important question of production management is the determination of the latest *start date* for BoM items to complete the order before the *due date*.

Normally production does not start from an idle state instead there is some work-in-process (WIP) e.g. in buffers, on conveyors or in machines. The modeller can decide to accept an initialisation phase until the model contains a certain amount of WIP to start the real experiment or initialise the model with work-in-process data.

Control. Control systems determine how products flow through the manufacturing processes, collect status information about products and/or resources, inspect the compliance of resource or demand constraints and decide about the use of the *restricted recourses*. A control algorithm can influence a simulation with changes of input data e.g. a changed

semi finished part order in an assembly line or changes in inwards and outwards goods movements in a *warehouse management* system. A *shop floor* or/and an *inventory control* algorithm can change model properties and model structure e.g. a storage area extension or reduction or an equipment layout modification of a manufacturing system. A *WIP tracking* system can deliver current process status information for control strategies. *Station rules* define local scheduling decisions, e.g. the working sequence in a manufacturing cell from simple first in, first out control strategy to a more complex such as a custom order dependant priority control strategy.

6.2.3 Measures of Performance

The methods to evaluate the performance of a real system and model have to be the same otherwise it will be difficult to have confidence in simulation and analysis results. Because both the real system and its model are based on random events the performance measure is a statistical analysis of real system and simulation system results. The following measurements are typical for a manufacturing system [51]:

- Throughput of sub model (such as a machine or process) or the complete model
- Cycle time at a process or overall
- Queueing time or length
- Response time of material handling equipment
- WIP
- Resource utilisation
- System specific performance measures (scrap rate, waiting time at a process etc.)

Due to the fact that a manufacturing system is a complex system it is important to note that model changes to improve one measure usually change other measures, for optimisation this is an important issue.

6.2.4 Analysis Issues

Using the measures described in chapter 5 an analyst experiments with a model to understand coherences of model elements and the behaviour of the whole system using input value, model parameter and model structure changes. Among others the following are typical analysis questions [51]:

- Determining bottlenecks
- Determining required staffing levels
- Evaluating the scheduling of staff
- Evaluating the scheduling of tasks
- Evaluating the control system
- Recovering strategies for random events

The identification of bottlenecks is often an analysis issue. The problem is the direct influence of the experiment on the bottleneck. With changes of anything in the model the primary bottleneck can move to other elements of the model. So the identification of a bottleneck can be a complex task and requires the examination at both local and global model levels.

A second important analysis issue is the determination of resource levels. Manufacturing systems with a fluctuating production volume, e.g. with seasonal dependencies, require such an analysis. An example is the staff requirement. It can change constantly and has to be planned regularly. An associated issue is the scheduling of staff between manufacturing system elements. With intelligent scheduling strategies it may be possible to employ fewer staff and still maintain sufficient throughput or to increase the throughput without increasing staff costs.

6.3 Introduction to the Photofinishing Industry

The application in this research uses developments and problems in the photofinishing industry and investigates a small part of a production process to validate the key research

concept. The photofinishing industry specialises in high volume production of thousands to millions of pictures per day but has nevertheless a relatively broad range of different products. As a consequence of significant changes in the photography market, notably the introduction of digital cameras with a considerable reduction of analogue and an increase of digital orders during recent years, a mix of analogue and digital production facilities are used. The change of the main production material from analogue to digital material has lead to concentration from many, local working, smaller laboratories to few, large, nationwide working laboratories and fierce competition between them. The situation is driving an urgent need to be as cost effective as possible.

Figure 6.3 shows general structure and product flow through the different departments of a typical photofinishing laboratory. It is possible to differentiate between three main production departments to depict the production flow analogue film/digital image – photographic picture:

I. The material arrives in several forms at the login process. After sorting the product mixes, some 10 to some 100 single orders are combined into batches. Each batch contains only one production material and one product type, e.g. undeveloped analogue film and specific paper width and surface. The batch creation is done with different machine types: (i) a splicer combines undeveloped film rolls onto a large film reel, (ii) a universal reorder station (URS) combines analogue reorders to a strap of film strips, (iii) a digital URS scans the analogue reorders and creates a digital batch, (iv) a digital splicer handles digital data carriers (CDs, flash cards etc.) and (v) software applications combine digital images collected by a web server. Steps (i) and (ii) creates analogue and steps (iii)...(v) digital batches.

II. Undeveloped analogue batches have to be developed. Analogue material can be scanned for the next steps which could be CD production and digital printing. As an alternative, the analogue batches are printed at an analogue printer. The result of both printer types is a huge reel of exposed photographic paper.

III. After the development of a photographic paper reel the final step is cutting. Regarding paper cutting both cutter and digital cutter are comparable. A DigiCutter is specialised for paper cutting without a film cutter but possibly equipped with several paper cutters each able to cut different paper widths. Finally items are packed and identified for delivery to customers.

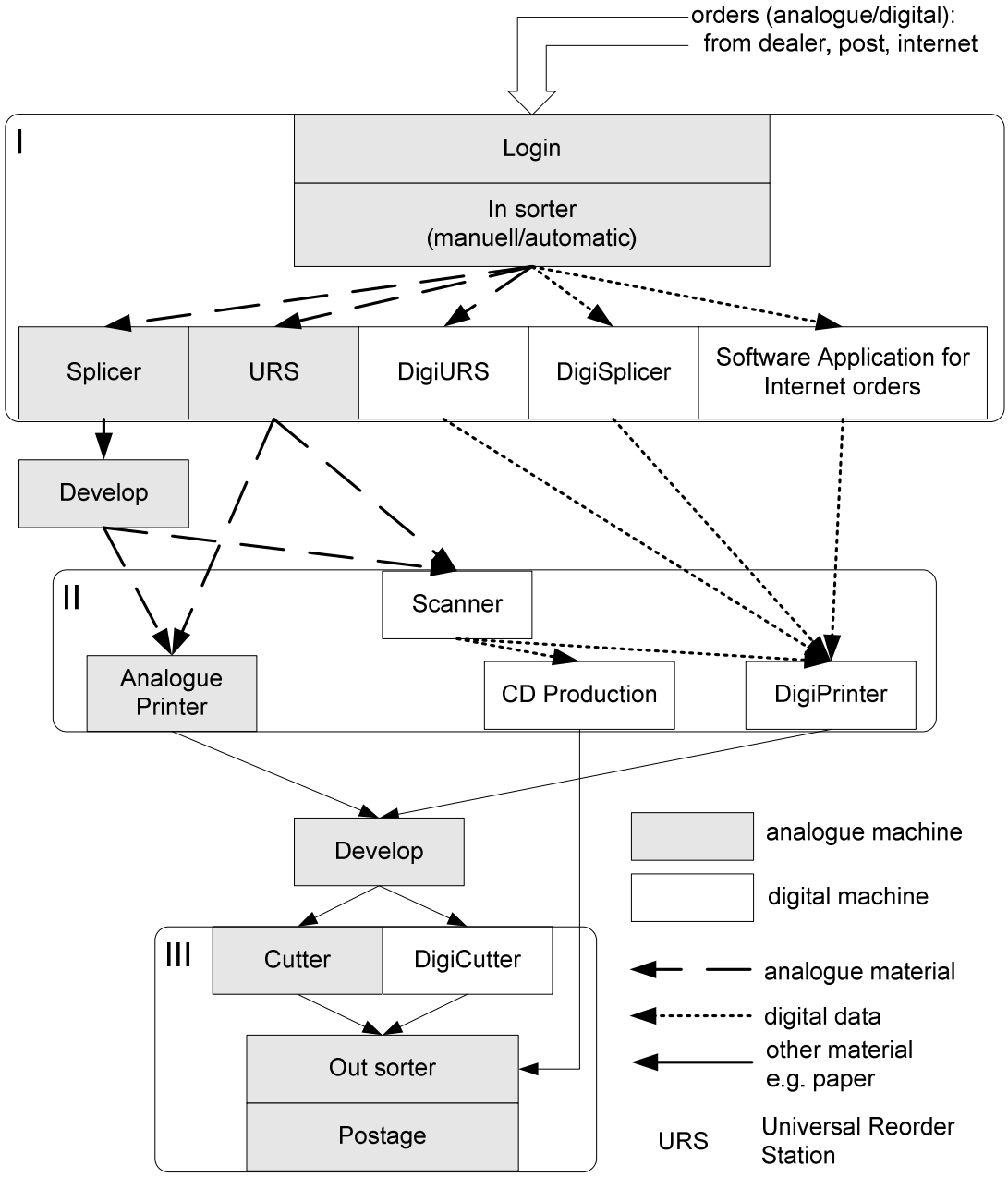


Figure 6.3 General product flows of a photofinishing lab

Figures C.1 ... C.4 in appendix C show a selection of photofinishing machines.

The product flow splicer/URS – development – analogue printer – development – cutter was the common production flow before the digital era and is typical serial manufacturing system. Nowadays there are several possible material routes through production with the same end product but different processing time, machine and operator requirements and costs i.e. a photofinishing lab now appears more as a job scheduling system. It is possible to employ fewer operators than available workstations and produce on time if an appropriate production structure and effective organization method are used to manage production. In a typical company with staff of some 10 to some 100, possibly more than one employee is necessary to organise the complete production.

6.4 Photofinishing Lab – An Optimisation Application

The validation is based on developments and problems in the photofinishing industry and investigates a small part of a production process to demonstrate the approach. The germ of the idea to this example comes from a project enquiry made by the Kodak Photofinishing Department (closed down) to Syntax Software [58] 6 years ago.

6.4.1 Problem Description

For this project the login and splicer departments are studied in detail with a structure as depicted in figure 6.4.

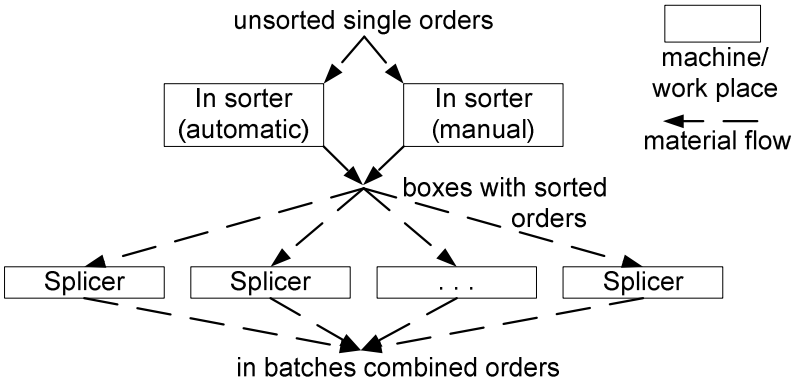


Figure 6.4 Product flow of the considered example

- System description

  The source materials, unsorted, single orders, are sorted by product type manually or automatically into boxes. These sorted orders are combined to batch reels at splicers. An automatic sorter is handled by one or two operators, whereas manual sorting is done by the number of available operators without the need of a machine. A splicer is handled by one operator. Operators can be moved between machines. The handling time of the machines is listed in table 6.2.

Machine	Order handling time (s)
automatic in sorter	0.5
manual in sorter	$1.7 \leq 2$ (equal distribution)
splicer	$0.9 \leq 1$ (equal distribution)

Table 6.2 Order handling times

  Sorting and splicing of a defined amount of orders takes a production time depending on type of machines, number of operators and organisation strategies. The production time is estimated by simulation.

  A specific production system causes costs. In this case study the costs depends on the number of operators as shown in table 6.3.

# of operators	Costs
1	1
2	2
3	3
4	4
5	5
6	6
7	7
8	8

Table 6.3 Production costs

- Simulation model level of detail and fundamental components

  Each workstation is taken as a black box with a defined processing time and resource utilisation. Workstations need a specific number of operators to manufacture and can be enabled or disabled. Further properties do not exit.

  Source material is modelled as a data structure with material type and planed end product type.

A production or department manager is modelled as a control model. The model can enable and disable workstations and organise material flow depending on the availability of operators, unhandled source material and queue lengths.

The number of operators is a model property used by the control model. Operators are moved between departments and workstations to enable and disable workstations. Operator movements does not cost any time.

To minimise complexity additional considerations e.g. setup time, maintenance and failure are not modelled. Shift schedules and other components in connection with operators are not modelled too.

- Performance Measurement

  For a performance measurement the sorting and splicing of a defined number of orders are simulated. The simulation output of a single run delivers the production time and cost $Y = \{y_{production\ time}, y_{costs}\}$ of the current model variant.

  The simulation response function calculates the average over 50 runs. They are passed to the objective function that is defined by the term:

  $$F = F(Y) = \alpha_1 * r_1 * \bar{y}_{production\ time} + \alpha_2 * r_2 * \bar{y}_{costs} \rightarrow \text{minimum}$$

  The factors α_1 and α_2 normalise the values of the variables, $\bar{y}_{production\ time}$ and $\bar{y}_{costs}$. The factors r_1 and r_2 define the relevance of the variables, $\bar{y}_{production\ time}$ and $\bar{y}_{costs}$. With the factors $\alpha_1 = 1/max\_production\_time$, $\alpha_2 = 1/max\_costs$, $r_1 = 1$ and $r_2 = 1$ both variables are within the range between 0 and 1 and have the same relevance. The maximal value of the production time can be calculated with a minimal production system i.e. one operator, manual sorting and one splicer. The maximal value of the costs is defined by the upper bound of the parameter *number of operators*. In this case study for both variables, $\bar{y}_{production\ time}$ and $\bar{y}_{costs}$ the same relevance is chosen. Depending on the analysis objectives a different relevance of $\bar{y}_{production\ time}$ and $\bar{y}_{costs}$ can be used.

  The result of the funtion *F* is the performance of the investigated model variant.

- Analysis issues

The production time and consequently the cost for a specific number of orders varies depending on the type and number of machines used, number of operators and the strategy to organise operators i.e. the initial distribution and succeeding movement of operators between machines and departments. The challenge for modelling is to minimise the combination of the production time of a given number of orders and the costs i.e. employing a minimal number of operators.

6.4.2 Implementation Details

Figure 6.5 shows the SES, describing possible model structures and the model parameter *number of operators*. Both the SES and the model parameter are the open quantities of the optimisation problem. The model structure variants are characterised by the use of: (i) automatic and/or manual sorting, (ii) one to eight splicers and (iii) one of three different department organisation strategies to share operators between machines and departments. Depending on selected alternative nodes during the pruning process several structure related attached variables will be initialised with different values. The SES defines 72 model structure variants in all. In addition there is one model parameter, the *number of operators* with a range of one to eight. The combination results in 576 model variants. Not all model variants define useful combinations. For example a model with four operators and eight splicers delivers the same result as a model with four operators and four splicers since in both variants only four splicers at all can be used. To exclude the useless variants the root node MODEL defines a structure condition that reduces the valid number of model variants to 275.

The following list describes the nodes and basic components, respectively:

- DEP_LOGIN

  The login department model can have three different sorting configurations. The first configuration applies only manual, the second only automatic and the third combines both sorting types. The number of available operators in this department is managed

by the $controller_{spec}$ model. Decisions of the $controller_{spec}$ model may be a function of the queue_order length.

- DEP_SPLICER

  The splicer department model can consist of a different number of splicers. The number of available operators in this department is managed by the $controller_{spec}$ model. Decisions of the $controller_{spec}$ model may be a function of the queue_box2 length.

- $controller_{spec}$

  The specialisation node $controller_{spec}$ has three successor nodes each implementing another staff organisation strategy:

  - ctrl1:

    The strategy starts with employing operators in the login department. If more staff is available than needed they are employed in the splicer department. After sorting is finished all staff is employed in the splicer department.

  - ctrl2:

    The strategy starts with employing operators in the login department. If more staff is available than needed they are employed in the splicer department. If the queue_box length is larger or equal than four all staff is employed in the splicer department. If the queue_box length is smaller than four the initial staff arrangement is recovered.

  - ctrl3:

    The strategy starts with employing half of operators in the login department and the other half in the splicer department. After sorting is finished all staff is employed in the splicer department.

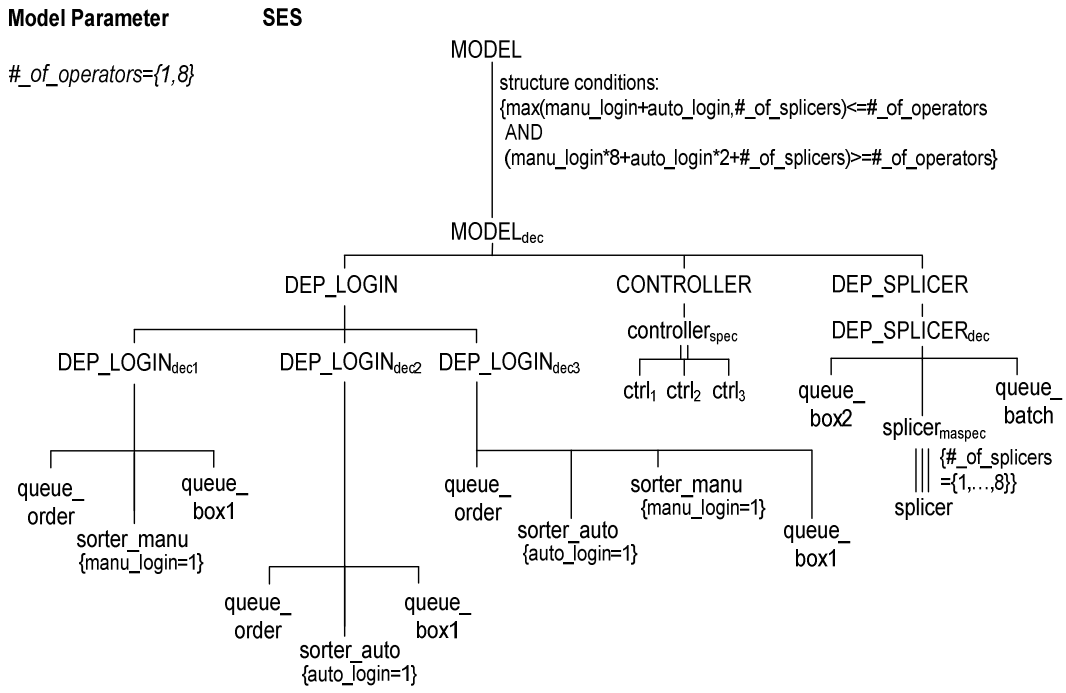


Figure 6.5 Model parameter and SES of the application

To solve this example, the search space has to be defined in terms of a structure parameter set, a model parameter set and their corresponding domain sets. Using the principle introduced in section 5.2 the structure parameter set and the corresponding domain set are defined by:

$X_S = \{x_{DEP\_LOGIN}, x_{controllerspec}, x_{splicermaspec}\}$

$D_S = \{d_{DEP\_LOGIN}, d_{controllerspec}, d_{splicermaspec}\}$ with

$d_{DEP\_LOGIN} = \{1; 2; 3\}$

$d_{controllerspec} = \{1; 2; 3\}$

$d_{splicermaspec} = \{1; 2; 3; 4; 5; 6; 7; 8\}$

The model parameter set and the corresponding domain set are defined by:

$X_P = \{x_{\#\_of\_operators}\}$

$D_P = \{d_{\#\_of\_operators}\}$ with $d_{\#\_of\_operators} = \{1; 2; 3; 4; 5; 6; 7; 8\}$

Hence, the resulting search space is defined by:

$X = X_P \cup X_S$

$X = \{ x_{DEP\_LOGIN}, x_{controllerspec}, x_{splicermaspec}, x_{\#\_of\_operators}\}$

Each model variant defines one point in the search space. With the principle introduced in section 5.2 a PES can be derived and a corresponding model can be generated. One point of the search space is $X_{132} = \{2; 2; 2; 2\}$. This means that the aspect node DEP_LOGIN_{dec2} and the specialisation $ctrl_2$ are chosen, the number range property value of the multiple aspect node $splicer_{maspec}$ is two and the model parameter *#_of_operators* is also two. Figure 6.6 depicts the PES of model variant 132. The generated EDSDEVS model is illustrated in figure 6.7.

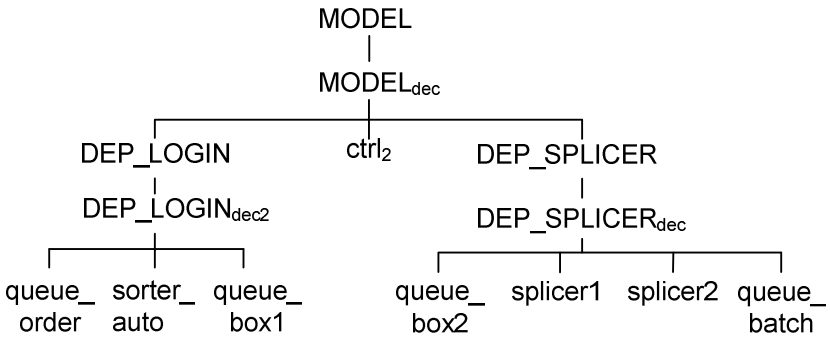


Figure 6.6 PES of 132th variant

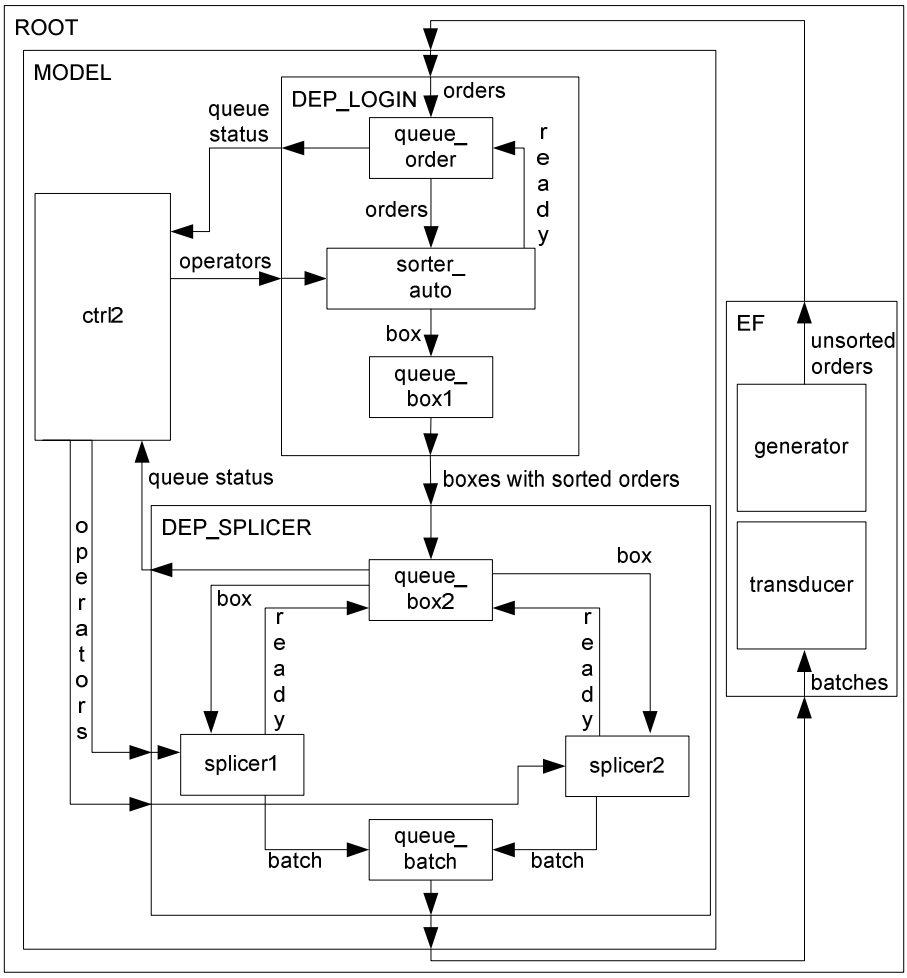


Figure 6.7 Model structure of 132th variant

All model variants use intensively the dynamic structure characteristics of the EDSDEVS formalism. The model of the department manager (model *ctrl2* in figure 6.7) activates and deactivates several atomic models (models *sorter_auto*, *splicer1* and *splicer2* in figure 6.7) and creates and destroys couplings respectively based on the department manager algorithm and the current model state. Figure 6.8 shows a sequence diagram section of one simulation run. Depending on queue lengths messages are generated and sent to the control model that enables/disables models and creates/destroys couplings.

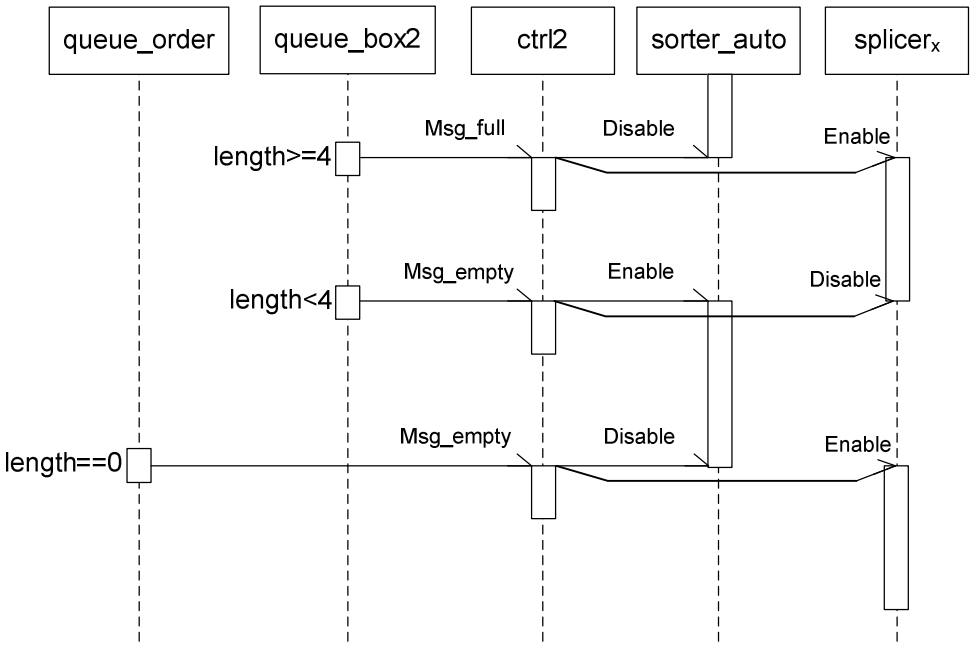


Figure 6.8 A sequence diagram section of one simulation run

Numerous commercial and non-commercial GA implementations exist. In this research the commercial toolbox MATLAB® GA toolbox [59] released by The MathWorks™ is used. The default MATLAB GA parameter settings were used, except for a decreased population size of 15 and an adjusted stop criterion:

if the weighted average change in the fitness function value over x generations (x=20 in 1st and x=5 in 2nd experiment) is less than 0.01, the algorithm stops.

In the following all GA parameters and their values are listed. A description and lists of possible values as well as the algorithm description can be found in [59].

Population:

- Population type: Double Vector
- Population size: 15
- Creation function: Uniform
- Initial population: []
- Initial scores: []
- Initial range: [0; 1]

Fitness scaling:

- Scaling function: Rank

Selection:

- Selection function:: Stochastic uniform

Reproduction:

- Elite count: 2
- Crossover fraction: 0.8

Mutation:

- Mutation function: Gaussian
- Scale: 1.0
- Shrink: 1.0

Crossover:

- Crossover function: Scattered

Migration:

- Direction: Forward
- Fraction: 0.2
- Interval: 20

Algorithm settings:

- Initial penalty: 10
- Penalty factor: 100

Hybrid function:

- Hybrid function: None

Stopping criteria:

- Generations: 100
- Time limit: Inf
- Fitness limit: -Inf
- Stall generations: 20 (1st experiment)

  5 (2nd experiment)

- Stall time limit: 20
- Function tolerance: 0.01
- Nonlinear constraint tolerance: 0.000001

Display to command window:

- Level of display: Final

Vectorize:

- Fitness function is vectorized: Off

The population size and the stop criteria are adapted for this case study. It is possible that changes of other parameters would lead to better optimisation results but further experiments are not undertaken in the scope of this research.

Each simulation run estimates the production time of 200 orders with a random production type mixture. The optimisation was repeated 50 times for each stop criterion with different random number generator initialisations. Listing 6.1 shows a Matlab code section of the optimisation initialising and executing the GA.

```
% ses tree is initialised outside of this function
function example_optim_exp(ses)

  % function uses two parameters, the ses object (global
  variable) and a search room point
  fitnessFunction = @exec_simu;

  % Bounds
  % e.g. LB = [  1 1 1 1 ];
  % e.g. UB = [  3 3 8 8 ];
  [LB UB] = ses.generateBounds();

  % Number of Variables
  nvars = size(LB,2);

  % Start with default options
  options = gaoptimset;

  % Modify some parameters
  options = gaoptimset(options,'PopulationSize' ,15);
  options = gaoptimset(options,'StallGenLimit' ,20); %1st exp.
  % options = gaoptimset(options,'StallGenLimit' ,5);%2nd exp.
  options = gaoptimset(options,'TolFun' ,0.01);

  % Run GA
  [X,FVAL,REASON,OUTPUT,POPULATION,SCORES] =
```

```
ga(fitnessFunction,nvars,Aineq,Bineq,Aeq,Beq,LB,UB,nonlconFu
nction,options);
```

Listing 6.1 Matlab code section with GA initialisation and execution

6.4.3 Results

To validate the research framework the global optimum estimated through simulation of all system variants is compared with the result of an optimisation experiment. In both experiments the performance rating of a variant is established by the same objective function using the following function definition:

$F = F(Y) = \alpha_1 * r_1 * \bar{y}_{production\ time} + \alpha_2 * r_2 * \bar{y}_{costs}$

$r_1 = r_2 = 1$ – same relevance of both paramters

$\alpha_1 = 1/566$ – maximal production time with a minimal production system is 566 (1st line in table 6.4)

$\alpha_2 = 1/8$ – maximal costs are 8

The simulation results of all 275 variants are shown in table 6.4. The columns control strategy, login and # of splicers specifies the model structure and the column # of operators specifies the model parameter as described in subsection 6.4.2. The production time values are the simulation result of the production of 200 orders. The costs correspond to the number of operators and the fitness is calculated with the above objective function.

ctrl strat.	login	# of splicer	# of ops	prod. time	costs	fitness
1	1	1	1	566,0	1	1,1250
1	1	1	2	357,0	2	0,8807
1	1	1	3	209,0	3	0,7443
1	1	1	4	208,0	4	0,8675
1	1	1	5	209,0	5	0,9943
1	1	1	6	208,0	6	1,1175
1	1	1	7	208,0	7	1,2425
1	1	1	8	207,0	8	1,3657
1	1	2	2	288,0	2	0,7588
1	1	2	3	208,0	3	0,7425
1	1	2	4	208,0	4	0,8675
1	1	2	5	207,0	5	0,9907
1	1	2	6	208,0	6	1,1175
1	1	2	7	209,0	7	1,2443
1	1	2	8	207,0	8	1,3657
1	1	3	3	209,0	3	0,7443
1	1	3	4	199,0	4	0,8516
1	1	3	5	208,0	5	0,9925
1	1	3	6	208,0	6	1,1175
1	1	3	7	208,0	7	1,2425
1	1	3	8	209,0	8	1,3693
1	1	4	4	208,0	4	0,8675
1	1	4	5	207,0	5	0,9907
1	1	4	6	208,0	6	1,1175
1	1	4	7	208,0	7	1,2425
1	1	4	8	208,0	8	1,3675
1	1	5	5	208,0	5	0,9925
1	1	5	6	197,0	6	1,0981
1	1	5	7	208,0	7	1,2425
1	1	5	8	208,0	8	1,3675
1	1	6	6	209,0	6	1,1193
1	1	6	7	208,0	7	1,2425
1	1	6	8	208,0	8	1,3675
1	1	7	7	198,0	7	1,2248
1	1	7	8	200,0	8	1,3534
1	1	8	8	208,0	8	1,3675
1	2	1	1	279,5	1	0,6188
1	2	1	2	229,5	2	0,6555
1	2	1	3	179,8	3	0,6926
1	2	2	2	139,75	2	0,4969
1	2	2	3	119,5	3	0,5861
1	2	2	4	99,5	4	0,6758
1	2	3	3	99,8	3	0,5512
1	2	3	4	89,5	4	0,6581
1	2	3	5	69,3	5	0,7474
1	2	4	4	79,3	4	0,6400
1	2	4	5	69,5	5	0,7478
1	2	4	6	59,8	6	0,8556
1	2	5	5	59,3	5	0,7297
1	2	5	6	59,5	6	0,8551
1	2	5	7	59,5	7	0,9801
1	2	6	6	59,8	6	0,8556
1	2	6	7	59,3	7	0,9797
1	2	6	8	59,3	8	1,1047
1	2	7	7	59,5	7	0,9801
1	2	7	8	59,5	8	1,1051
1	2	8	8	59,5	8	1,1051
1	3	1	2	219,5	2	0,6378
1	3	1	3	204,0	3	0,7354
1	3	1	4	189,8	4	0,8352
1	3	1	5	149,5	5	0,8891
1	3	1	6	160,0	6	1,0327
1	3	1	7	159,5	7	1,1568
1	3	1	8	169,5	8	1,2995
1	3	2	2	149,3	2	0,5137
1	3	2	3	124,0	3	0,5941
1	3	2	4	119,5	4	0,7111
1	3	2	5	109,8	5	0,8189
1	3	2	6	89,8	6	0,9086
1	3	2	7	89,8	7	1,0336
1	3	2	8	79,8	8	1,1409
1	3	3	3	104,0	3	0,5587
1	3	3	4	99,8	4	0,6762
1	3	3	5	89,5	5	0,7831
1	3	3	6	69,8	6	0,8732
1	3	3	7	59,5	7	0,9801
1	3	3	8	59,8	8	1,1056
1	3	4	4	79,8	4	0,6409
1	3	4	5	79,8	5	0,7659
1	3	4	6	69,8	6	0,8732
1	3	4	7	59,8	7	0,9806
1	3	4	8	60,0	8	1,1060
1	3	5	5	69,5	5	0,7478
1	3	5	6	59,5	6	0,8551
1	3	5	7	59,5	7	0,9801
1	3	5	8	49,5	8	1,0875
1	3	6	6	59,8	6	0,8556
1	3	6	7	59,8	7	0,9806
1	3	6	8	50,0	8	1,0883
1	3	7	7	49,8	7	0,9629
1	3	7	8	49,8	8	1,0879
1	3	8	8	49,8	8	1,0879
2	1	1	1	404,0	1	0,8388
2	1	1	2	265,0	2	0,7182
2	1	1	3	309,0	3	0,9209
2	1	1	4	329,0	4	1,0813
2	1	1	5	330,0	5	1,2080
2	1	1	6	329,0	6	1,3313
2	1	1	7	328,0	7	1,4545
2	1	1	8	308,0	8	1,5442
2	1	2	2	213,0	2	0,6263
2	1	2	3	214,0	3	0,7531
2	1	2	4	219,0	4	0,8869
2	1	2	5	227,0	5	1,0261
2	1	2	6	228,0	6	1,1528
2	1	2	7	237,0	7	1,2937
2	1	2	8	237,0	8	1,4187
2	1	3	3	191,0	3	0,7125
2	1	3	4	208,0	4	0,8675
2	1	3	5	209,0	5	0,9943
2	1	3	6	205,0	6	1,1122
2	1	3	7	218,0	7	1,2602
2	1	3	8	208,0	8	1,3675
2	1	4	4	183,0	4	0,8233
2	1	4	5	197,0	5	0,9731
2	1	4	6	192,0	6	1,0892
2	1	4	7	210,0	7	1,2460
2	1	4	8	190,0	8	1,3357
2	1	5	5	187,0	5	0,9554
2	1	5	6	196,0	6	1,0963
2	1	5	7	190,0	7	1,2107
2	1	5	8	200,0	8	1,3534
2	1	6	6	191,0	6	1,0875
2	1	6	7	189,0	7	1,2089
2	1	6	8	202,0	8	1,3569
2	1	7	7	187,0	7	1,2054
2	1	7	8	183,0	8	1,3233
2	1	8	8	192,0	8	1,3392
2	2	1	1	271,0	1	0,6038
2	2	1	2	253,8	2	0,6983

2	2	1	3	215,8	3	0,7562
2	2	2	2	133,5	2	0,4859
2	2	2	3	161,0	3	0,6595
2	2	2	4	135,5	4	0,7394
2	2	3	3	104,3	3	0,5592
2	2	3	4	140,3	4	0,7478
2	2	3	5	105,0	5	0,8105
2	2	4	4	94,0	4	0,6661
2	2	4	5	104,8	5	0,8101
2	2	4	6	95,8	6	0,9192
2	2	5	5	83,8	5	0,7730
2	2	5	6	106,3	6	0,9377
2	2	5	7	85,3	7	1,0256
2	2	6	6	74,0	6	0,8807
2	2	6	7	90,8	7	1,0353
2	2	6	8	75,3	8	1,1330
2	2	7	7	74,3	7	1,0062
2	2	7	8	88,5	8	1,1564
2	2	8	8	74,8	8	1,1321
2	3	1	2	244,3	2	0,6815
2	3	1	3	202,3	3	0,7323
2	3	1	4	187,0	4	0,8304
2	3	1	5	184,3	5	0,9505
2	3	1	6	204,0	6	1,1104
2	3	1	7	194,8	7	1,2191
2	3	1	8	194,0	8	1,3428
2	3	2	2	133,8	2	0,4863
2	3	2	3	145,0	3	0,6312
2	3	2	4	119,8	4	0,7116
2	3	2	5	115,8	5	0,8295
2	3	2	6	115,0	6	0,9532
2	3	2	7	115,0	7	1,0782
2	3	2	8	114,8	8	1,2027
2	3	3	3	87,3	3	0,5292
2	3	3	4	113,5	4	0,7005
2	3	3	5	99,3	5	0,8004
2	3	3	6	96,0	6	0,9196
2	3	3	7	94,0	7	1,0411
2	3	3	8	84,8	8	1,1497
2	3	4	4	72,5	4	0,6281
2	3	4	5	107,5	5	0,8149
2	3	4	6	78,5	6	0,8887
2	3	4	7	76,5	7	1,0102
2	3	4	8	75,0	8	1,1325
2	3	5	5	62,8	5	0,7359
2	3	5	6	93,8	6	0,9156
2	3	5	7	78,0	7	1,0128
2	3	5	8	65,3	8	1,1153
2	3	6	6	62,8	6	0,8609
2	3	6	7	80,5	7	1,0172
2	3	6	8	67,8	8	1,1197
2	3	7	7	53,8	7	0,9700
2	3	7	8	79,0	8	1,1396
3	1	1	1	566,0	1	1,1250
3	1	1	2	394,0	2	0,9461
3	1	1	3	209,0	3	0,7443
3	1	1	4	208,0	4	0,8675
3	1	1	5	209,0	5	0,9943
3	1	1	6	208,0	6	1,1175
3	1	1	7	208,0	7	1,2425
3	1	1	8	207,0	8	1,3657
3	1	2	2	406,0	2	0,9673
3	1	2	3	208,0	3	0,7425
3	1	2	4	208,0	4	0,8675
3	1	2	5	207,0	5	0,9907
3	1	2	6	208,0	6	1,1175
3	1	2	7	209,0	7	1,2443
3	1	2	8	207,0	8	1,3657
3	1	3	3	209,0	3	0,7443
3	1	3	4	199,0	4	0,8516
3	1	3	5	208,0	5	0,9925
3	1	3	6	208,0	6	1,1175
3	1	3	7	208,0	7	1,2425
3	1	3	8	209,0	8	1,3693
3	1	4	4	208,0	4	0,8675
3	1	4	5	207,0	5	0,9907
3	1	4	6	208,0	6	1,1175
3	1	4	7	208,0	7	1,2425
3	1	4	8	208,0	8	1,3675
3	1	5	5	208,0	5	0,9925
3	1	5	6	197,0	6	1,0981
3	1	5	7	208,0	7	1,2425
3	1	5	8	208,0	8	1,3675
3	1	6	6	209,0	6	1,1193
3	1	6	7	208,0	7	1,2425
3	1	6	8	208,0	8	1,3675
3	1	7	7	198,0	7	1,2248
3	1	7	8	200,0	8	1,3534
3	1	8	8	208,0	8	1,3675
3	2	1	1	279,5	1	0,6188
3	2	1	2	189,0	2	0,5839
3	2	1	3	179,8	3	0,6926
3	2	2	2	149,5	2	0,5141
3	2	2	3	119,5	3	0,5861
3	2	2	4	99,5	4	0,6758
3	2	3	3	99,8	3	0,5512
3	2	3	4	89,5	4	0,6581
3	2	3	5	89,3	5	0,7827
3	2	4	4	79,3	4	0,6400
3	2	4	5	79,5	5	0,7655
3	2	4	6	69,8	6	0,8732
3	2	5	5	69,3	5	0,7474
3	2	5	6	69,5	6	0,8728
3	2	5	7	69,5	7	0,9978
3	2	6	6	59,8	6	0,8556
3	2	6	7	59,3	7	0,9797
3	2	6	8	59,3	8	1,1047
3	2	7	7	59,5	7	0,9801
3	2	7	8	59,5	8	1,1051
3	2	8	8	59,5	8	1,1051
3	3	1	2	179,0	2	0,5663
3	3	1	3	189,5	3	0,7098
3	3	1	4	189,5	4	0,8348
3	3	1	5	164,0	5	0,9148
3	3	1	6	154,3	6	1,0225
3	3	1	7	159,5	7	1,1568
3	3	1	8	169,5	8	1,2995
3	3	2	2	148,5	2	0,5124
3	3	2	3	119,5	3	0,5861
3	3	2	4	99,3	4	0,6754
3	3	2	5	84,0	5	0,7734
3	3	2	6	84,0	6	0,8984
3	3	2	7	89,8	7	1,0336
3	3	2	8	79,8	8	1,1409
3	3	3	3	99,5	3	0,5508
3	3	3	4	79,5	4	0,6405
3	3	3	5	84,0	5	0,7734
3	3	3	6	74,0	6	0,8807
3	3	3	7	59,5	7	0,9801
3	3	3	8	59,8	8	1,1056
3	3	4	4	79,5	4	0,6405
3	3	4	5	74,0	5	0,7557

3	3	4	6	64,0	6	0,8631
3	3	4	7	59,8	7	0,9806
3	3	4	8	60,0	8	1,1060
3	3	5	5	64,0	5	0,7381
3	3	5	6	54,0	6	0,8454
3	3	5	7	59,5	7	0,9801
3	3	5	8	49,5	8	1,0875
3	3	6	6	54,0	6	0,8454
3	3	6	7	59,8	7	0,9806
3	3	6	8	50,0	8	1,0883
3	3	7	7	49,8	7	0,9629
3	3	7	8	49,8	8	1,0879
3	3	8	8	49,8	8	1,0879

Table 6.4 Simulation results of all model structure and parameter variants with resulting production time, costs and fitness

The fitness values of all 275 model variants are shown graphically in figure 6.9.

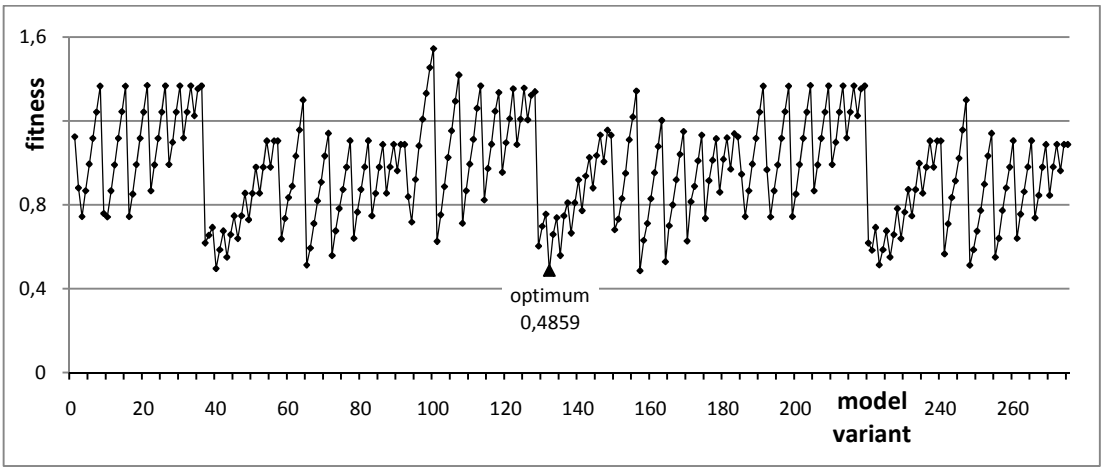


Figure 6.9 Fitness values of all variants with the optimum at X_{132}

The limits of the objective function parameters i.e. model generation and simulation results and objective function results are shown in table 6.5. The solution X_{132} has the minimal fitness value 0.4859 i.e. this solution is the global optimum. Figure 6.6 shows the PES and figure 6.7 the model structure of this variant.

	min	max
production time	49,5	566
costs	1	8
fitness	0.4859	1,5442

Table 6.5 Limits of fitness function parameters and results

Beside the global minimum several local minima exist with a very close fitness value, as can be seen in figure 6.9. Table 6.6 lists the global optimum (green line) and all near optimal solutions with a maximal variation of 3% of the maximal fitness value of 2. The solutions 2, 4 and 7 are identical to solutions 1, 3 and 6 due to the preferred assignment of the two available operators to the automatic login i.e. the manual login is not used in variants 2, 4, 7. The solutions 1, 3 and 6 differ in the control strategy whereas the most flexible control strategy 2 delivers the optimal result. Solutions 3 and 5 are based on different system configurations. With the used same weighting of production time and costs the solution 3 is the optimal solution, with a higher weighting of production time solution 5 would be a better variant.

no.	ctrl strat.	login typ	# of splicers	# of ops		prod. time	costs		fittness
1	1	2	2	2		139,8	2		0,4969
2	1	3	2	2		149,3	2		0,5137
3	2	2	2	2		133,5	2		0,4859
4	2	3	2	2		133,8	2		0,4863
5	2	3	3	3		87,3	3		0,5291
6	3	2	2	2		149,5	2		0,5141
7	3	3	2	2		148,5	2		0,5124

Table 6.6 Optimal and near optimal solutions

With other relevance factors r_1 and r_2 the optimal system configuration is different. E.g. without the consideration of costs two global optima with a production time of 49.5 exist (X_{86} and X_{267}). These solutions produce the specified number of orders in the shortest time.

In each of the two GA optimisation experiments the optimisation was repeated 50 times to estimate average values because of the stochastic nature of GA. Each optimisation experiment uses one stop criterion as described in section 6.4.2.

The results with average number of investigated individuals, optimum and near optima found are shown in table 6.7. The results show that the number of investigated individuals (194 and 102) is significant less than the number of all variants (275). The probability to find the optimal or near optimal solution is high (68% and 50%) but the finding is not guaranteed. Both, the number of investigated individuals and the finding probability depend highly on chosen GA parameters as can be seen when comparing the results of optimisation experiment 1 and 2 in table 6.7.

	Stop criterion 1 (uses weighted average change over 20 generation)	Stop criterion 2 (uses weighted average change over 5 generation)
Average number of investigated individuals to find an optimum	194	102
Optimum X_{132}	47%	21%
Near optimal results with max 3.2% error	21%	29%

Table 6.7 Results of 50 optimisation experiments

An example of the development of individual fitness values, best and average generation fitness during a single optimisation experiment is shown in figure 6.10. The diagram shows the fast convergence of the average fitness of the generations. After two generations each generation contains the optimal solution once in minimum and after the 7th generation the fitness value does not change anymore.

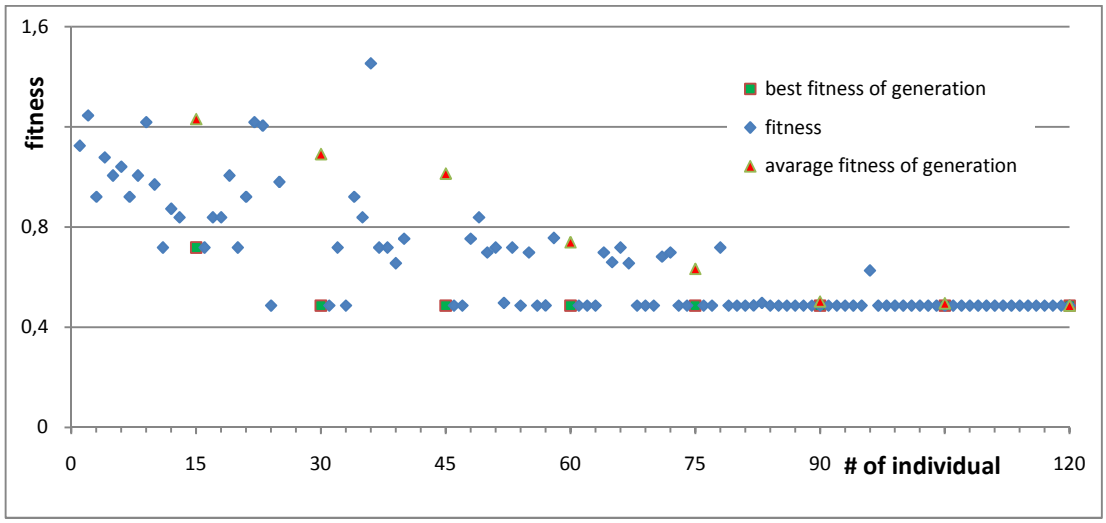


Figure 6.10 Individual fitness, best and average fitness of generations of one GA run

The results show that the optimisation approach developed in this research delivers an optimal solution with a high probability and with significantly less simulation runs in comparison to a complete simulation study of all model variants. Consequently the new approach of a simulation based parameter and structure optimisation is validated with a first real industrial example. There is a potential to increase the probability and/or decrease the number of simulation runs to estimate the optimal solution through adaptations of the GA parameters or with the use of other search methods.

For a potential application of the introduced approach it is necessary to extend the model to a complete Photofinishing Laboratory. Although the model of the case study is relative small the computing time of an optimisation experiment is on average between some 10 minutes and a few hours. However, the case study is carried out with a prototypical implementation of the simulation method and ideal parallelisation possibilities of GAs are not used. Hence, it can be assumed that there is a huge potential of runtime optimisation.

The introduced case study stands for many flexible production systems. It can be assumed that the developed framework can be applied to other, comparable systems with the ability of modular, hierarchical modelling.

Chapter 7

Conclusions and further Work

7.1 Conclusions

Simulation in a manufacturing context focuses on modelling the behaviour and the structure of manufacturing organisations, processes and systems. Many manufacturing systems have the potential to be optimised and to exploit this potential simulation based optimisation techniques are an important step forward. The overall goal of applying of these techniques is the identification of improved user selected system parameters. This research deals with a fundamental optimisation problem in discrete event simulation. Optimisation is well established but restricted to the optimisation of system parameters. Model structure is considered to be fixed, defined during model development. In simulation based optimisation using automated model parameter changes and manual model structure adaptations the global optimal system configuration cannot be guaranteed. With the growing use of flexible manufacturing systems and the increasing demand for product customisation the number of manufacturing system variants increases consequently the demand for structure optimisation is becoming increasingly more important.

This research has developed a simulation based optimisation method to solve the limitations of the established techniques. A crucial difference to established simulation based parameter optimisation is the application of a method based on meta-modelling to manage a set of models. The new optimisation method can simultaneously control both model

parameter changes and model structure selection. The result of a successful optimisation experiment using this approach is a parameter and structure optimised model. The key research aim to develop an approach to replace conventional manual structural changes i.e. to develop a combined, simulation based parameter and structure optimisation has been achieved.

An essential prerequisite of the new approach is a modular, hierarchical modelling and simulation method with a strict separation of model and simulator. This research determined the DEVS formalism as a suitable method. DEVS as a two-part definition consisting of a formal model specification and a simulation algorithm to model execution was introduced in the 70s and since then has been continuously developed. Many DEVS extensions have one joint attribute: they are based on the original DEVS formalism and have not taken advantage of the potential in combining extensions. For this reason the research has been followed the idea of a merging formalism to combine the advantages of different approaches. The new EDSDEVS formalism developed from this research is a fusion of Classic DEVS with selected extensions. It is an as generic as possible, powerful modelling and simulation formalism based on DEVS. A second key research aim to develop a modelling and simulation method based on DEVS and DEVS extensions to create a merging formalism has been achieved.

A further prerequisite for simulation based optimisation is an appropriate model management method. This research determined the SES/MB approach as a suitable method. Originally the SES/MB framework was developed to assist an analyst during a manual model variant selection. Changes to the SES/MB approach and algorithms to embed it into the simulation based optimisation have been developed within the research.

The final prerequisite is a suitable search method to find the optimal model configuration in the general multidimensional search space. Many search algorithms exist. One category widely used in both research and commercial applications are genetic and

evolutionary algorithms. For a practical investigation of the fundamental simulation based parameter and structure optimisation framework a commercial GA is used.

Validation of the work has been achieved using an industrial problem where the ability to control manufacturing system structure is an important optimisation factor. The photo-processing industry relies on management of the process flow to achieve profitability and this application demonstrates both how the new framework functions and the validity of the GA used in a real world situation. In two optimisation experiments it has been shown that the results are significantly dependent on the GA parameters. However in both experiments the probability to find an optimal or near-optimal model configuration is equal to or greater than 50%. An increased probability of an optimal solution is preferable however this will be the subject of further work.

The framework is implemented as MATLAB toolboxes and uses a commercial GA toolbox respectively. In the prototypical implementation of the framework and the validation of the work it has been shown that the use of MATLAB has both advantages and disadvantages. It is a powerful and productive environment to solve scientific and engineering problems and to implement prototypical applications. A disadvantage is the interpretative operation method. Particularly in simulation based optimisation where numerous, time consuming simulation runs lead to long execution times. However, there are parallel computing MATLAB toolboxes which support several aspects of parallelisation. The algorithmic summary shown using a GA is a promising approach to improve execution time by parallelisation.

During the research project the important steps have been published in a peer-reviewed journal, at international conferences and as a book chapter. Appendix C presents the publications.

7.2 Suggestions for further work

This research has established an approach to simulation based parameter and structure optimisation. Whilst this thesis presents the ideas, principles and a first example, it also opens up several future research directions. Future research directions can be divided into two areas (i) investigations of simulation based optimisation framework (ii) EDSDEVS formalism.

i. The introduced approach defines the model structure variants at the meta-model level as a static structure. Otherwise it uses a dynamic structure modelling and simulation method to execute the selected model configuration. The dynamic changes of the model structure during the simulation time are not considered in this approach i.e. the optimisation regards only the initial model structure as a static structure. It seems feasible to add dynamic structure changes during the model lifetime as an additional criterion to the optimisation. An example is the length of stay of a sub model. This approach considers the initial existence of the sub model but its lifetime may play an important role in the search for an optimal model configuration.

   With the SES XML definition a platform and implementation independent meta-modelling definition already exists. The manual modelling based on direct writing a XML file is not straightforward. General XML editors can assist the modelling but cannot replace a dedicated SES XML editor. A graphical SES/MB modelling application is a reasonable extension.

   As already shown in section 6.4.3 the optimisation results and the number of optimisation cycles depends on the GA parameters. There is much literature about GA methods and parameterisation. The experience gained in this research has shown that further investigations in this direction are necessary. Hence, the optimisation of GA parameters is a further research topic.

There are also other promising search methods. Another nature analogue method is the Particle Swarm Optimisation (PSO) approach based on swarm intelligence of social groups. This group of algorithms is relative new, introduced around 10 years ago. The number of publications and applications is growing fast. The literature review has shown evidence that this algorithm group can solve problems like the simulation based optimisation as well as GAs.

ii. The new EDSDEVS formalism developed from this research is a fusion of Classic DEVS with several extensions. This part of the research is a step to a generic modelling and simulation formalism based on DEVS. Further extensions are desirable and essential e.g. extensions for parallel computing and graphical modelling. There are also approaches for hybrid DEVS extensions i.e. the support of continuous state changes. These are proposals for further research. The last proposal, the hybrid DEVS, is already a current research project topic of the Research Group CEA.

The importance and topicality of the idea behind this research can be seen in two brand new research proposals, the first currently in preparation and the second announced at 30.03.2009:

A research proposal at the Deutsche Forschungsgemeinschaft (DFG German Research Foundation) for further developments of the simulation based parameter and structure optimisation approach and its application to the optimisation of energy efficiency of process chains and manufacturing structures is currently in preparation. The optimisation of energy efficiency of process chains i.e. among other things the structure optimisation of process chains is a planned priority programme of DFG.

In a call for proposal of the Federal Ministry of Education and Research of Germany a sponsorship is announced with the topic ‘safeguarding competitiveness by versatile manufacturing systems’. One matter of the proposed research is covered by the optimisation technique introduced in this thesis.

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Appendix B. Coding Examples

atomic_model

variables:

t_{last} *time of last event*

s internal state

function init()

// initialise state variable set S and t_{next} *with the time of the first internal event*

end function

function $\delta_{ext}(e, x)$

$t = t_{last} + e$

// do something with x.value

end function

function $\delta_{int}(t)$

$S_K \rightarrow S_{K+1}$ *// calculate next internal state* S_{K+1} *from current internal state* S_K

end function

function t = ta()

t = . . . // calculate next internal state event

end function

function $y = \lambda()$

y.value = . . . // set value of y-message

end function

end atomic_model

Listing B.1 Pseudo code skeleton of an atomic Classic DEVS model

```
coupled_model
    function M_d* = select(imminent)
        M_d* = . . .  // choose one of the sub component from component list imminent
    end function
end coupled_model
```

Listing B.2 Pseudo code skeleton of a coupled Classic DEVS model

variables:

t *simulation clock*

t_{end} *simulation end time*

when receive start-msg(t_{end})

send i-msg() to sub-ordinate DEVS coordinator

t := t_{next} of sub-ordinate coordinator

while t < t_{end}

*send *-msg(t) to sub-ordinate DEVS coordinator*

t := t_{next} of sub-ordinate coordinator

Listing B.3 Pseudo code of a Classic DEVS root coordinator

variables:

t_{last} *time of last event*

t_{next} *time of next internal state event*

am associated atomic model

when receive i-msg()

am.init()

$t_{last} := 0$

$t_{next} := am.ta()$

*when receive *-msg(t) at time t*

if $t <> t_{next}$

error: bad synchronisation

$y := am.\lambda()$

send y in y-message to parent coordinator

$am.\delta_{int}(t)$

$t_{last} := t$

$t_{next} := t_{last} + am.ta()$

when receive x-msg(t, x) at time t with value x

if not $(t_{last} \leq t \leq t_{next})$

error: bad synchronisation

$am.\delta_{ext}(t-t_{last}, x)$

$t_{last} := t$

$t_{next} := t_{last} + am.ta()$

Listing B.4 Pseudo code of a Classic DEVS simulator

variables:

t_{last} *time of last event*

t_{next} *time of next internal state event*

CM associated coupled model

when receive i-msg()

foreach sub component $M_d \in CM.M$

send i-msg() to M_d

$t_{last} := 0$

// determine time of next scheduled internal state event of all sub components

$t_{next} := min(\{ M_d.t_{next} \mid M_d \in CM.M \})$

*when receive *-msg(t) at time t*

if $t <> t_{next}$

error: bad synchronisation

// find all sub components with a true condition $t_{next}=t$

$imminent := \{ M_d \mid M_d \in CM.M \wedge M_d.\ t_{next}= t \}$

*// call select function to determin one sub component to send the *-msg*

$M_{d*} := select(imminent)$

*send *-msg(t) to* M_{d*}

$t_{last} := t$

// determine time of next scheduled internal state event of all sub components

$t_{next} := min(\{ M_d.t_{next} \mid M_d \in CM.M \})$

when receive x-msg(t, x) at time t with value x

if not $(t_{last} \leq t \leq t_{next})$

error: bad synchronisation

// get all sub components M_{d*} *with an appropriate EIC*

$receivers := subcomponents \{M_d \mid M_d \in CM.M\}$ *with* $\{coupling \mid coupling \in CM.EIC\}$

// forwards the x-msg to all appropriate sub components

foreach sub component M_{d*} *in receivers*

send x-msg(t, x) to M_{d*}

$t_{last} := t$

// determine time of next scheduled internal state event of all sub components

$t_{next} := min(\{M_d.t_{next} \mid M_d \in CM.M\})$

when receive y-msg(t, y) at time t with value y

// forwards y-msg to super-ordinate model if an appropriate EOC exists

if exist coupling in CM.EOC

send y-msg(t, y) to parent model

// get all sub components M_{d*} *with an appropriate IC*

receivers := subcomponents $\{M_d \mid M_d \in CM.M\}$ *with* $\{coupling \mid coupling \in CM.IC\}$

// creates from y-msg and sends it as an x-msg to all appropriate sub components

foreach sub component M_{d*} *in receivers*

send x-msg(t, $y \rightarrow x$*) to* M_{d*}

Listing B.5 Pseudo code of a Classic DEVS coordinator

```
atomic_model
    variables:
        t_last   time of last event
        s        internal state
    function δ_ext(e, x)
        t = t_last + e
        switch x.port
            case inputport_0
                // do something with x.value received at input port inputport_0
                . . .
            case inputport_n
                // do something with x.value received at input port inputport_n
                . . .
        end switch
    end function
    function  y = λ()
        y.port = . . .  // set output port of y-message
        y.value = . . . // set value of y-message
    end function
```

Listing B.6 Pseudo code skeleton of an atomic Classic DEVS with Ports model

*when receive *-msg(t) at time t*

if t <> t_{next}

error: bad synchronisation

y := am.λ()

send value y.value in y-message to parent coordinator ***at port y.port***

am.δ_{int}(t)

t_{last} := t

t_{next} := t_{last} + am.ta()

when receive x-msg(t, x, ***p****) at time t with value x* ***at port p***

if not ($t_{last} \leq t \leq t_{next}$)

error: bad synchronisation

am.δ_{ext}(t-t_{last}, x, ***p****)*

t_{last} := t

t_{next} := t_{last} + am.ta()

Listing B.7 Pseudo code of a Classic DEVS with Ports simulator

*when receive x-msg(t, x, **p**) at time t with value x **at port p***

if not ($t_{last} \leq t \leq t_{next}$)

error: bad synchronisation

// get all sub components M_{d*} with an appropriate EIC

receivers := subcomponents {M_d | $M_d \in$ CM.M} with {coupling | coupling$\in$ CM.EIC}

// forwards the x-msg to all appropriate sub components

foreach sub component M_{d*} in receivers

*send x-msg(t, x, **M_{d*}.p**) to M_{d*} **at port p***

$t_{last} := t$

// determine time of next scheduled internal state event of all sub components

$t_{next} := min(\{M_d.t_{next} \mid M_d \in CM.M\})$

*when receive y-msg(t, y, **p**) at time t with value y **at port p***

// forwards y-msg to super-ordinate model if an appropriate EOC exists

if exit coupling in CM.EOC

// coupling is a structure with the elements {sub component, p_{source}, $p_{destination}$}

foreach coupling in CM.EOC

*send y-msg(t, y, **coupling.$p_{destination}$**) to parent model*

// get all sub components M_{d*} with an appropriate IC

receivers := subcomponents {M_d |$M_d \in$ CM.M} with {coupling | coupling$\in$ CM.IC}

// creates x-msg from y-msg and sends it as an x-msg to all appropriate

sub components

foreach sub component M_{d*} in receivers

foreach coupling in CM.IC with coupling between y.source and M_{d*}.p

*send x-msg(t, y$\rightarrow$x, **M_{d*}.p**) to M_{d*} **at port p***

Listing B.8 Pseudo code of a Classic DEVS with Ports coordinator

atomic_model

variables:

t_{last} *time of last event*

s internal state

function init()

// initialise state variable set S and t_{next} *with the time of the first internal state event*

end function

function δ_{con}***(t, x_bag)***

// default implementation of a confluent function matches Classic DEVS functionality

δ_{int}***(t)***

δ_{ext}***(0, x_bag)***

end function

function δ_{ext}*(e,* ***x_bag****)*

$t = t_{last} + e$

foreach x in x_bag

// do something with x.value

end function

function δ_{int}*(t)*

$S_K \rightarrow S_{K+1}$ *// calculate next internal state* S_{K+1} *from current internal state* S_K

end function

function t = ta()

t = . . . // calculate next internal state event

end function

function ***y_bag*** *=* λ*()*

```
            y.value = . . . // set value of y-message
            y_bag += y
        end function
end atomic_model
```

Listing B.9 Pseudo code skeleton of an atomic PDEVS model

*when receive *-msg(t) at time t*

if t <> t_{next}

error: bad synchronisation

y_bag := am.λ()

send y_bag in y-message to parent coordinator

when receive x-msg(t, ***x_bag****) at time t with* ***x_bag***

if not ($t_{last} \leq t \leq t_{next}$)

error: bad synchronisation

if t=t_{next} and x_bag is not empty

// concurrent external and internal event

am.δ_{con}(t, x_bag)

else if t=t_{next} and x_bag is empty

// internal event

am.δ_{int}(t)

else

// external event

am.δ_{ext}(t-t_{last}, x_bag)

end if

t_{last} := t

t_{next} := t_{last} + am.ta()

Listing B.10 Pseudo code of a PDEVS simulator

atomic_model

variables:

t_{last} *time of last event*

s internal state

function init(t)

// initialise state variable set S and t_{next} *with the time of the first internal state event*

// t=0 initialisation at simulation start

// t>0 initialisation after structure change

end function

function $\delta_{con}(t, x\_bag)$

// default implementation of a confluent function matches Classic DEVS functionality

$\delta_{int}(t)$

$\delta_{ext}(0, x\_bag)$

end function

function $\delta_{ext}(e, x\_bag)$

$t = t_{last} + e$

foreach x in x_bag

// do something with x.value received at x.port

switch x.port

case $inputport_0$

// do something with x.value received at input port $inputport_0$

. . .

case $inputport_n$

// do something with x.value received at input port $inputport_n$

```
            . . .
        end switch
    end function
    function δ_int(t)
        s_u → s_{u+1}  // calculate next internal state s_{u+1} from current internal state s_u
    end function
    function  t = ta()
        t = . . .       // calculate next internal state event
    end function
    function  y_bag = λ()
        y.value = . . . // set value of y-message
        y.port = . . . // set output port of y-message
        y_bag += y
    end function
end atomic_model
```

Listing B.11 Pseudo code skeleton of an atomic EDSDEVS model

```
coupled_model
    variables:
        t_last   time of last event
        s        internal state
    function  init(t)
        // initialise structure and state variable set S and t_next with the time of the first
           internal
        //  state event
        // t=0 initialisation at simulation start
        // t>0 initialisation after structure change
     end function
    function  δ_con(t, x_bag)
        // default implementation similar to an atomic model
          functionality
        δ_int(t)
        δ_x&s(0, x_bag)
    end function
    function δ_x&s(e, x_bag)
        t = t_last + e
        foreach x in x_bag
            // do something with x.value received at x.port
            switch x.port
                    case inputport_0
                            // do something with x.value received at input port inputport_0
                            . . .
                    case inputport_n
```

```
                    // do something with x.value received at input port inputport_n
                    . . .
                end switch
            end function
            function  δ_int(t)
                s_u → s_u+1  // calculate next internal state s_u+1 from current internal state s_u
            end function
            function  t = ta()
                t = . . .       // calculate next internal state event
            end function
            function  y_bag = λ(t)
                y.value = . . . // set value of y-message
                y.port = . . . // set output port of y-message
                y_bag += y
            end function
end coupled_model
```

Listing B.12 Pseudo code skeleton of a coupled EDSDEVS model

variables:

t_{last} *time of last event*

t_{next} *time of next internal state event*

am associated atomic model

when receive i-msg(t)at time t

// t=0 initialisation at simulation start

// t>0 initialisation after structure change

am.init(t)

$t_{last} := t$

$t_{next} := am.ta()$

*when receive *-msg(t) at time t*

if $t <> t_{next}$

error: bad synchronisation

$y\_bag := am.\lambda()$

send y_bag in a y-message to parent coordinator

when receive x-msg(t, x_bag) at time t with value x_bag containing x.value und x.port pairs

if not $(t_{last} \leq t \leq t_{next})$

error: bad synchronisation

if $t=t_{next}$ *and x_bag is not empty*

// concurrent external and internal event

$am.\delta_{con}(t, x\_bag)$

else if $t=t_{next}$ *and x_bag is empty*

// internal event

$am.\delta_{int}(t)$

else

// external event

$am.\delta_{ext}(t-t_{last}, x\_bag)$

end if

$t_{last} := t$

$t_{next} := t_{last} + am.ta()$

Listing B.13 Pseudo code of an EDSDEVS simulator

variables:

t_{last} *time of last event*

t_{next} *time of next internal state event of the coupled model or a sub component*

t_{next_c} *time of next internal state event of the coupled model*

CM associated atomic model

// CM.s_t *current, sequential structure state*

IMM // imminent children

mail // output mail bag

// t=0 initialisation at simulation start

// t>0 initialisation after structure change

when receive i-msg(t)at time t

CM.init(t)

foreach sub component $M_d \in CM.s_t.M$

send i-msg(t) to M_d

$t_{last} := t$

// determine time of next scheduled internal state event of coupled model

$t_{next\_c} := CM.ta()$

// determine time of next scheduled internal state event of coupled model and all

// sub components

$t_{next} := min(t_{next\_c}, \{ M_d.t_{next} \mid M_d \in CM.s_t.M \})$

*when receive *-msg(t) at time t*

if $t <> t_{next}$ & $t <> t_{next\_c}$

error: bad synchronisation

// internal state transition event of the coupled model CM itself

if $t=t_{next\_c}$

$y\_bag := CM.\lambda()$

send bag of value/output port pairs in a y-message to parent coordinator

// internal state transition event of a sub component of CM

else if $t=t_{next}$

// find all sub components with a true condition $t_{next}=t$

$IMM := \{ M_d \mid M_d \in CM.s_t.M \wedge M_d.\ t_{next} = t \}$

foreach M_d *in IMM*

*send *-msg(t) to* M_d

when receive x-msg(t, x_bag) at time t with value x_bag containing pairs of x.value/x.port

if not $(t_{last} \le t \le t_{next\_c})$

error: bad synchronisation

if $t=t_{next\_c}$ *and x_bag is not empty*

$CM.\delta_{con}$*(t, x_bag) // concurrent external and internal event*

else if $t=t_{next\_c}$ *and x_bag is empty*

$CM.\delta_{int}$*(t) // internal event*

else

$CM.\delta_{x\&s}$*(t-*t_{last}*, x_bag) // external event*

end if

// get all sub components M_{d*} *with an appropriate EIC*

receivers := subcomponents $\{M_d \mid M_d \in CM.s_t.M\}$ *with* $\{coupling \mid coupling \in CM.s_t.EIC\}$

// forwards the x-msg to all appropriate sub components

foreach sub component M_{d*} *in receivers*

$CM.\delta_{x\&s}$*(t-*t_{last}*, x_bag) // external event of sub component*

send x-msg(t, x_bag, $M_{d*}.p$*) to* M_{d*} *at port p*

foreach sub component M_{d*} *in IMM and not in receivers*

send x-msg(t, NULL, NULL) to M_{d*} *// send empty bag, input port is ignored*

$t_{last} := t$

$t_{next\_c} := t_{last} + CM.ta()$

$t_{next} := min(t_{next\_c}, \{ M_d.t_{next} \mid M_d \in CM.s_t.M \})$

when receive y-msg(t, y_bag, d) at time t with y_bag with value/port pairs from d

// collect all y-messages from all sub components

if d is not the last not reporting d in IMM

add (y_bag, d) to mail

mark d in IMM as reporting

*// all sub components now handled their *-message*

else if d is the last not reporting d in IMM

$CM.\delta_{x\&s}(t-t_{last}, mail)$

// check external coupling to form sub-bag of parent output

$y\_bag_{parent} = NULL$

foreach d in mail where (y_bag and d) has an appropriate EIC

add y_bag to y_bag_{parent}

send y-msg(t, y_bag_{parent}*, CM) to parent model*

// check IC to get children M_{d*} *with an appropriate IC who receives a sub bag*

receivers := subcomponents $\{M_d \mid d$ *in mail,* $M_d \in CM.s_t.M\}$ *with* $\{coupling \mid coupling \in CM.s_t.IC\}$

foreach sub component M_{d*} *in receivers*

creates sub bag x_bag from mail with elements where M_{d*} *is receiver*

send x-msg(t, x_bag) to M_{d*}

mark d in IMM as sending

foreach sub component M_{d*} *in IMM where* M_{d*} *is not sending*

send x-msg(t, NULL) to M_{d*}

$t_{last} := t$

$t_{next\_c} := t_{last} + CM.ta()$

$t_{next} := min(t_{next\_c}, \{ M_d.t_{next} \mid M_d \in CM.s_t.M \})$

Listing B.14 Pseudo code of an EDSDEVS coordinator

```
<?xml version="1.0" encoding="us-ascii"?>
<!--
    DTD for an SES.
-->

<!ELEMENT top (ses_mb)>

<!ELEMENT ses (modelbase | ses | properties)*>

<!ELEMENT modelbase ((mb_composite | mb_atomic | mb_aspect |
mb_specialization | mb_specializationentity | mb_multiAspect)+)>

<!ELEMENT ses (composite)>

<!ELEMENT properties ((modelcouplings | var | varNumberOfComponent |
constraint)+)>

<!ELEMENT modelcouplings ((eic | eoc | ic)+)>
<!ATTLIST modelcouplings
      esname CDATA #REQUIRED>

<!ELEMENT mb_composite EMPTY>
<!ATTLIST mb_composite
      esname CDATA #REQUIRED>

<!ELEMENT composite ((aspect | specialization | multiAspect)*)>
<!ATTLIST composite
      esname CDATA #REQUIRED>


<!ELEMENT mb_atomic ((inports | outports)*)>
<!ATTLIST mb_atomic
      esname CDATA #REQUIRED
      classname CDATA #REQUIRED
      modelname CDATA #REQUIRED>

<!ELEMENT atomic EMPTY>
<!ATTLIST atomic
      esname CDATA #REQUIRED>


<!ELEMENT mb_aspect ((inports | outports)*)>
<!ATTLIST mb_aspect
      esname CDATA #REQUIRED
      classname CDATA #REQUIRED
      modelname CDATA #REQUIRED>

<!ELEMENT aspect ((entity | specialization | multiAspect |
atomic)*)>
<!ATTLIST aspect
      esname CDATA #REQUIRED>


<!ELEMENT mb_specialization ((inports | outports)*)>
<!ATTLIST mb_specialization
      esname CDATA #REQUIRED>

<!ELEMENT mb_specializationentity EMPTY>
<!ATTLIST mb_specializationentity
      esname CDATA #REQUIRED
```

```
      classname CDATA #REQUIRED
      modelname CDATA #REQUIRED>

<!ELEMENT specialization (specializationentity+)>
<!ATTLIST specialization
      esname CDATA #REQUIRED>

<!ELEMENT specializationentity EMPTY>
<!ATTLIST specializationentity
      esname CDATA #REQUIRED>


<!ELEMENT mb_multiAspect EMPTY>
<!ATTLIST mb_multiAspect
      esname CDATA #REQUIRED>

<!ELEMENT multiAspect (atomic)>
<!ATTLIST multiAspect
      esname CDATA #REQUIRED>


<!--
internal var will be set internally in the ses
external var references an external variable
-->
<!ELEMENT var EMPTY>
<!ATTLIST var
      name CDATA #REQUIRED
      esname CDATA #REQUIRED
      typ (internal|external) "internal"
      external_name CDATA #IMPLIED
      value CDATA #IMPLIED>

<!ELEMENT varNumberOfComponent EMPTY>
<!ATTLIST varNumberOfComponent
      esname CDATA #REQUIRED
      min CDATA #REQUIRED
      max CDATA #REQUIRED>

<!ELEMENT inports (inport+)>

<!ELEMENT outports (outport+)>

<!ELEMENT inport EMPTY>
<!ATTLIST inport
      name CDATA #REQUIRED>

<!ELEMENT outport EMPTY>
<!ATTLIST outport
      name CDATA #REQUIRED>

<!ELEMENT eic EMPTY>
<!ATTLIST eic
      inport CDATA #REQUIRED
      component CDATA #REQUIRED
      component_inport CDATA #REQUIRED>

<!ELEMENT eoc EMPTY>
<!ATTLIST eoc
      component CDATA #REQUIRED
```

```
      component_outport CDATA #REQUIRED
      outport CDATA #REQUIRED>

<!ELEMENT ic EMPTY>
<!ATTLIST ic
      component1 CDATA #REQUIRED
      component1_outport CDATA #REQUIRED
      component2 CDATA #REQUIRED
      component2_inport CDATA #REQUIRED>

<!ELEMENT constraint EMPTY>
<!ATTLIST constraint
      name CDATA #REQUIRED
      typ (entity|parameter) #REQUIRED
      action (enable|valid) #IMPLIED
      condition (gt|lt|eq|gteq|lteq|neq) #IMPLIED
      var_name1 CDATA #IMPLIED
      var_name2 CDATA #IMPLIED
      destination CDATA #IMPLIED>
```

Listing B.15 DTD describing the structure of SES/MB XML

```
<?xml version="1.0" encoding="utf-8"?>
<!DOCTYPE ses SYSTEM "ses.dtd" []>
<ses_mb>
  <ses>
    <composite esname="ROOT">
      <aspect esname="ROOTdec">
        <composite esname="A">
          <specialization esname="Aspec">
                <specializationentity esname="A1"/>
                <specializationentity esname="A2"/>
          </specialization>
        </composite >
        <composite esname="B">
          <aspect esname="Bdec">
                <atomic esname="D"/>
                <atomic esname="E"/>
          </aspect>
        </composite >
      </aspect>
    </composite >
  </ses>

  <modelbase>
    <mb_aspect esname="ROOTdec" classname="ROOT" modelname="root"/>
    <mb_specialization esname="Aspec">
      <outports>
        <outport name="Aout1"/>
        <outport name="Aout2"/>
      </outports>
    </mb_specialization>
    <mb_aspect esname="Bdec" classname="B" modelname="b">
      <inports>
        <inport name="Bin1"/>
        <inport name="Bin2"/>
      </inports>
      <outports><outport name="Bout"/></outports>
    </mb_aspect>
    <mb_atomic esname="D" classname="D" modelname="d">
      <inports><inport name="Din"/></inports>
      <outports><outport name="Dout"/></outports>
    </mb_atomic>
    <mb_atomic esname="E" classname="E" modelname="e">
      <inports>
        <inport name="Ein1"/>
        <inport name="Ein2"/>
      </inports>
      <outports><outport name="Eout"/></outports>
    </mb_atomic>
  </modelbase>

  <properties>
    <modelcouplings esname="ROOTdec">
      <ic component1="A" component1_outport="Aout1"
           component2="B" component2_inport="Bin1"/>
      <ic component1="A" component1_outport="Aout2"
           component2="B" component2_inport="Bin2"/>
    </modelcouplings>
    <modelcouplings esname="Bdec">
      <eic inport="Bin1" component="D" component_inport="Din"/>
      <eic inport="Bin2" component="E" component_inport="Ein2"/>
```

```
        <ic component1="D" component1_outport="Dout"
          component2="E" component2_inport="Ein1"/>
        <eoc component="E" component_outport="Eout" outport="Bout"/>
      </modelcouplings>
      <var esname="ROOT" name="pmax" typ="internal" value="6"/>
      <var esname="A1" name="p1" typ="internal" value="2"/>
      <var esname="A2" name="p1" typ="internal" value="3"/>
      <var esname="D" name="p2" typ="internal" value="3"/>
      <constraint name="sc1" condition="lt" var_name1="p1+p2"
                  var_name2="pmax" action="valid" typ="parameter"/>
    </properties>
</ses_mb>
```

Listing B.16 SES/MB XML example – XML file

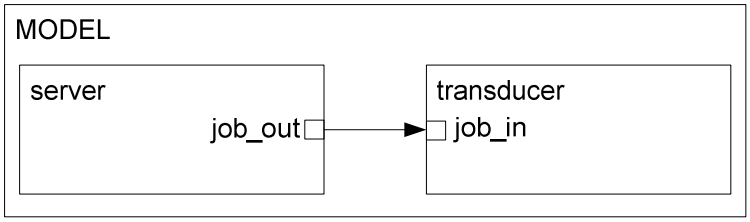

Figure B.1 A coupled model example

```
<?xml version="1.0" encoding="utf-8"?>
<atomic modelName="server" xmlns="AtomicDevs">
  <inports/>
  <outports>
    <outport>job_out</outport>
  </outports>
</atomic>

<?xml version="1.0" encoding="utf-8"?>
<atomic modelName="transducer" xmlns="AtomicDevs">
  <inports>
    <inport>job_in</inport>
  </inports>
  <outports/>
</atomic>
```

Listing B.17 Two atomic model XML files

```
<?xml version="1.0" encoding="utf-8"?>
<coupled modelName="MODEL" xmlns="CoupledDevs">
  <Models>
    <Model><devs>server</devs></Model>
    <Model><devs>transducer</devs></Model>
  </Models>
  <inports/>
  <outports/>
  <EIC/>
  <IC>
    <Coupling>
      <SrcModel>server</SrcModel><outport>job_out</outport>
      <DestModel>transducer</DestModel>
  <inport>job_in</inport>
    </Coupling>
  </IC>
  </EOC>
</coupled>
```

Listing B.18 Coupled model XML file

0. Define the search space and chose an appropriate information encoding in chromosomes
1. Initialise a population of individuals with different chromosomes (generation 0)

Repeat until stop criterion is fulfilled

2. Estimate the fitness of all individuals of the current generation
3. Select pairs with *m* individuals and create descendants using crossover
4. Mutate the descendants
5. Exchange individuals of the current generation with descendants based on a substitution schema to create a new generation

Listing B.19 A general GA algorithm

Appendix C. Photofinishing Machines

Figure C.1 Splicer (left) and URS

Figure C.2 DigiURS (left) and High-speed film scanner

Figure C.3 Analogue (left) and digital printer

Figure C.4 Manual (left) and automatic cutter

Appendix D. Publications in the Course of this Research

Hagendorf O., Pawletta T. (2009) *Extended Dynamic Structure DEVS*. Proceedings of the 21st European Modeling and Simulation Symposium (submitted and accepted).

Hagendorf O., Pawletta T. (2009) *A Framework for Simulation Based Structure and Parameter Optimization of Discrete Event Systems*. book project by CRC Press, editor: G. Wainer and P. Mosterman, 30 pages (submitted and accepted 2008/2009) .

Hagendorf O. Pawletta T. (2008) *An Approach for Simulation Based Structure Optimisation of Discrete Event Systems.* Proceedings of the 2008 Spring Simulation Conference.

Hagendorf O., Pawletta T., Pawletta S., Colquhoun G. (2006) *An approach for modelling and simulation of variable structure manufacturing systems.* ICMR 2006 Liverpool/UK.

Pawletta T., Deatcu C., Pawletta S., Hagendorf O., Colquhoun G. (2006) *DEVS-Based Modeling and Simulation in Scientific and Technical Computing Environments.* Proceedings of the 2006 Spring Simulation Conference DEVS/HPC/MMS 2006 Huntsville/Al USA.

Hagendorf O., Colquhoun G., Pawletta T., Pawletta S. (2005) *A DEVS - Approach to ARGESIM Comparison C16 'Restaurant Business Dynamics' using MatlabDEVS.* Simulation News Europe, no.44/45, (December).

EXTENDED DYNAMIC STRUCTURE DEVS

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ABSTRACT
Since the first publication of DEVS, the formalism was enhanced and many extensions have been introduced. Every extension holds some advantages over the other, e.g. Parallel DEVS generalizes the specification and handling of concurrent events, DEVS with Ports enables a more structured modeling and Dynamic Structure DEVS introduces dynamic structure changes at coupled model level during simulation time. The extensions have one joint attribute: they are extending the Classic DEVS formalism and don't incorporate the advantages of each other. Hence, the decision on one DEVS extension inhibits the use of advantages of another one. This lack leads to the idea of a merging formalism to combine the advantages of different approaches. The Extended Dynamic Structure DEVS combines the Classic DEVS with some of the existing extensions: Parallel DEVS, Dynamic Structure DEVS and DEVS with Ports.

Keywords: Discrete Event Simulation, DEVS, DSDEVS, PDEVS, EDSDEVS

1. INTRODUCTION

The DEVS formalism was first introduced by Zeigler (Zeigler 1976) in the 1970s. In (Zeigler et.al. 2000) the authors classify this formalism, position and compare it with other, more established modeling and simulation formalisms. Several international research groups are working on the DEVS formalism and are regularly publishing results at the annual DEVS Symposium at Spring Simulation Conferences, European Modeling and Simulation Symposia and others. Wainer (Wainer 2009) maintains a list of available DEVS tools. The DEVS formalism is, in contrast to other modeling and simulation formalisms, not very widely used in industrial practice. This situation persists despite the fact that the theory is a well-founded, general formalism. It can only be assumed that one reason of the marginal acceptance is the type of available software tools (Pawletta et.al. 2006).

There are several publications to extend the application field or to ease the use of DEVS e.g. Parallel DEVS generalizes the specification and handling of concurrent events, DEVS with Ports enables a more structured modeling and Dynamic Structure DEVS introduces dynamic structure changes at coupled model level during simulation time and significantly eases the modeling of larger real systems. The extensions have one joint attribute: they are based on the Classic DEVS formalism and extending it in a specific direction. Hence, the decision on one DEVS extension inhibits the use of advantages and application fields of another one. This lack leads to the idea of a merging formalism to combine the advantages of different approaches and widen the application field of the resulting formalism.

The Classic DEVS formalism with the formal modeling concept and simulation algorithms is introduced in chapter 2. After a short introduction of a few DEVS extensions, three of them are described in detail in chapter 3. The fusion of Classic DEVS with the introduced extensions to the new Extended Dynamic Structure DEVS approach is presented with formal concept, simulation principles and algorithms in chapter 4. The conclusions in chapter 5 complete this contribution.

2. CLASSIC DEVS

DEVS is a modular, hierarchical modeling and simulation formalism. Every DEVS model can be described by using two different model types, atomic and coupled. Both model types have an identical, clearly defined interface through input and output ports. An atomic model describes the behavior of a non-decomposable entity via input/output events and event driven state transition functions. A coupled model describes the structure of a more complex model through the aggregation of several entities and their couplings. These entities can be atomic models as well as coupled models. The DEVS formalism consists of two parts: (i) a formal DEVS model definition and (ii) simulator algorithms.

2.1. Formal Concept

The formal Classic DEVS description defines coupled and atomic models as a combination of sets and functions. The description of an atomic model is a 7-tuple (Zeigler et.al. 2000):

$am = (X, Y, S, \delta_{ext}, \delta_{int}, \lambda, ta)$

- X, Y and S specify the sets of discrete inputs, outputs and internal states.
- δ_{ext}: $Q \times X \rightarrow S$ where $Q = \{(s,e) \mid s \in S,$

$0<e<t_{next}\}$

The external state transition function δ_{ext} handles external input events.

- δ_{int}: $S \rightarrow S$
  The internal state transition function δ_{int} establishes a new internal state.
- λ: $S \rightarrow Y$
  The output function λ generates an output event depending on the internal state *S*.
- *ta*: $S \rightarrow \Re_0^+ \cup \infty$
  The time advance function *ta* schedules the time of the next internal event after each state transition.

Figure 1 shows the dynamic behavior of an atomic model.

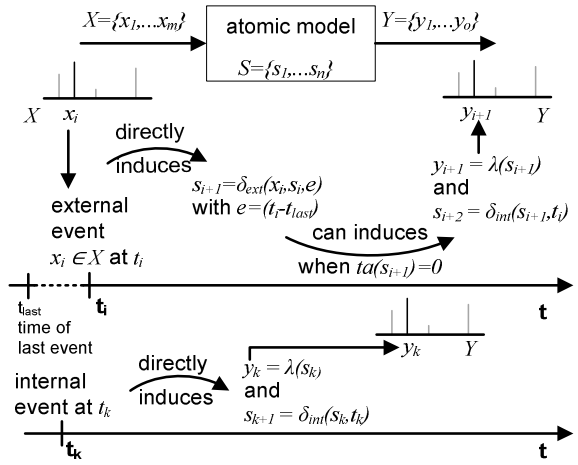


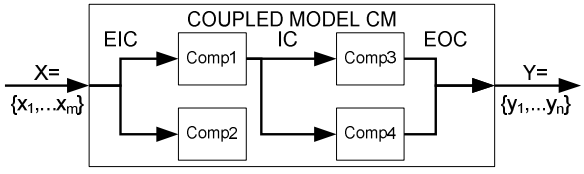
Fig. 1 Dynamic Behavior of an Atomic Model

The description of a coupled model is a 9-tuple (Zeigler et.al. 2000):

CM = (d_n, X, Y, D, { M_d }, EIC, EOC, IC, SELECT)

- d_n specifies the name of the coupled model.
- *X* and *Y* specify the sets of discrete inputs and outputs.
- *D* specifies the set of sub component names.
- $M_d \mid d \in D$
  M_d is the model of the sub component *d*
- *EIC*, *EOC* and *IC* are the sets of external input, external output and internal couplings.
- The *SELECT* function prioritizes concurrent internal events of sub components.

Figure 2 depicts the relations of the elements of a Classic DEVS coupled model.



EIC = {{CM.X,Comp1.X} {CM.X,Comp2.X}}
IC = {{Comp1.Y,Comp3.X} {Comp1.Y,Comp4.X}}
EOC = {{Comp3.Y,CM.Y} {Comp4.Y,CM.Y}}
D = {"Comp1", "Comp2", "Comp3", "Comp4"}

Fig. 2 Coupled Model Elements

The Classic DEVS approach supports the specification of behavioral system dynamics in atomic systems and the specification of static component aggregations in coupled systems. It is not possible to describe structural system dynamics at the coupled model level, i.e. the deletion or creation of components and couplings or changes of interfaces, although all necessary structural information is also available during simulation time. The only possibility to realize a structural system dynamic is to specify it with logical constructs at the atomic model level. However, this removes the advantages of reusability and model clarity and increases modeling complexity.

2.2. Classic DEVS Simulation

Beside the formal definition the second part of the Classic DEVS formalism is the description of abstract simulator algorithms for the execution of DEVS models. The algorithms are named abstract because they are implemented as a general pseudo code. The abstract simulator has a modular, hierarchical structure matching exactly the modular, hierarchical structure of a DEVS model. A DEVS model can be directly transformed into an executable simulator model using abstract simulator elements e.g. as shown in (Praehofer 1992; Zeigler et.al. 2000).

The abstract simulator approach consists of three different elements namely root coordinator, coordinator and simulator. Each atomic model is associated with a simulator element and each coupled model is associated with a coordinator element. The root coordinator is added to that structure as topmost ruling entity.

3. DEVS EXTENSIONS

Extensions of the Classic DEVS formalism increase the classes of system models that can be represented by DEVS. Several DEVS extensions are introduced e.g. in (Barros 1996; Chow et.al. 1994; Hagendorf et.al. 2006; Pawletta et.al. 1996; Praehofer 1992; Uhrmacher et.al. 1994; Wainer 2009; Zeigler et.al. 2000). An incomplete list of DEVS extensions recently presented is:

- DEVS with Ports: The port extension adds additional input and output ports to models.
- Parallel DEVS: Parallel DEVS (PDEVS) considers concurrent transition events.
- Dynamic Structure DEVS: Dynamic Structure DEVS (DSDEVS) enables changes during a simulation run. Several partial very different approaches exist. Dynamic structure extensions introduced by Barros (Barros 1996) and Pawletta (Pawletta et.al. 1996) keep the general structure of Classic DEVS modeling and simulation with additions to coupled model definitions but unchanged atomic model definitions. Other dynamic structure extensions e.g. an agent based DEVS (Uhrmacher et.al. 1994) introduce more extensive modifications.
- DSDEVS-hybrid: The extension of discrete state changes by continuous state changes as introduced by DSDEVS-hybrid enables a complete new

application field and can ease the modeling of several problems (Deatcu et.al. 2009).

- Real Time DEVS: The DEVS model is executed in real time rather than in model time. The time advance function delivers time intervals which allow uncertainty when an internal event has to take place.

The next sections introduce some of these DEVS extensions in more detail. They are used as basis of the subsequently introduced, unifying DEVS formalism.

3.1. DEVS with Ports

The introduction of ports into the Classic DEVS formalism makes modeling easier and the representation of information flow more clearly (Zeigler et.al. 2000). In Classic DEVS each model has only one single input and one single output port. All events are received and sent through these ports. With the port extension, a model has several input and output ports each dedicated for a specific task i.e. event type. A model can have several output ports which can be connected to input ports of other models as shown in figure 3. Hence, each event can use a dedicated, well defined routing path. The modeling becomes more structured; a model can become clearer and better understandable through differentiated interfaces.

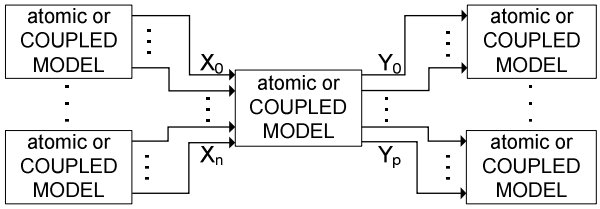


Fig. 3 Model with Multiple Input and Output Ports

The formal description of Classic DEVS with Ports largely remains the same except the extended definitions of *X, Y* for atomic and coupled models (Zeigler et.al. 2000):

$X = \{(p,v) \mid p \in \text{InputPorts}, v \in X_p\}$

$Y = \{(p,v) \mid p \in \text{OutputPorts}, v \in Y_p\}$

- *p* is the input or output port of the model
- *v* is a discrete value
- X_p / Y_p specify discrete inputs/outputs sets at port *p*

Whereas in Classic DEVS the coupling definitions consist of a sub model name as destination and source, respectively, for EIC and EOC and of a pair of sub model names for IC, the port extension necessitates a coupling definition extension, too:

- EIC = { (*input_port*, *d.input_port*) | *input_port* ∈ *InputPorts*, $d \in D$, *d.input_port* ∈ *InputPorts of* M_d }
- IC = { (d_i.*output_port*, d_k.*input_port*) | $d_i, d_k \in D$, d_i.*output_port* ∈ *OutputPorts of* M_{d_i}, d_k.*input_port* ∈ *InputPorts of* M_{d_k}, $i <> k$ }
- EOC = { (*d.output_port*, *output_port*) | *d.output_port* ∈ *OutputPorts of* M_d, $d \in D$, *output_por* ∈ *OutputPorts*}

3.2. Parallel DEVS

Parallel DEVS (PDEVS) was introduced by Chow (Chow et.al 1994). It adds new elements and functions to the Classic DEVS formalism. It allows all imminent components to be activated simultaneously and enables sending their output to other components at the same time concurrently. Multiple outputs are combined in a bag which is sent as a whole to a model's external state transition function. A bag is similar to a set, containing an unordered set of elements, but allows multiple occurrences of an element. In Classic DEVS by contrast events are handled individually. In a PDEVS simulator (Zeigler et.al. 2000) during the *-message handling first all outputs are established before calling external and internal state transition functions. Each receiving component is responsible for examining and interpreting its combined inputs in the correct order. PDEVS gives the atomic model more control over the handling order of concurrent external and internal events. In Classic DEVS a super-ordinate component, the coupled model, is responsible for the execution order of concurrent internal events of different sub components using the *select* function. In PDEVS the order of simultaneous events is locally controllable at atomic model level with an additional, third state transition function, the confluent transition function δ_{con}. Hence, it merges the decision logic of execution order of concurrent events with the event handling functions at a same level.

According to the extensions of PDEVS an atomic model is defined by the following 8- tuple (Chow et.al. 1994):

$am = (X, Y, S, \delta_{ext}, \delta_{int}, \delta_{con}, \lambda, ta)$

- *X*, *Y* and *S* specify the sets of discrete input events, output events and sequential states.
- δ_{ext}: $Q \times X^b \rightarrow S$ where X^b is a bag covering elements of *X* and $Q = \{ (s,e) \mid s \in S, 0<e<t_{next} \}$
  The external state transition function δ_{ext} handles a bag covering external inputs $X^b = \{x_i \mid x_i \in X\}$.
- δ_{int}: $S \rightarrow S$
  The internal state transition function δ_{int} establishes a new internal state.
- δ_{con}: $S \times X^b \rightarrow S$
  The confluent transition function δ_{con} handles the execution sequence of δ_{int} and δ_{ext} functions during concurrent external and internal events.
  - The confluent function definition $\delta_{con}(s, X^b) = \delta_{ext}(\delta_{int}(s), 0, X^b)$ with $\delta_{ext}(s, e, X^b)$ is equivalent to the Classic DEVS behavior with a higher prioritized handling of internal events.
  - The alternative confluent function defintion $\delta_{con}(s, X^b) = \delta_{int}(\delta_{ext}(s, ta(s), X^b))$ with $\delta_{int}(s)$ first handles external events.
  - The execution of the confluent function with an empty bag $\delta_{con}(s, null)$ calls directly the internal transition function δ_{int}.
- λ: $S \rightarrow Y^b$ where Y^b is a bag covering elements of *Y*

The output function λ generates a bag covering outputs $Y^b = \{ y_i \mid y_i \in Y \}$ depending on the internal state *S*.

- *ta:* $S \rightarrow \Re_0^+ \cup \infty$
  The time advance function *ta* schedules the time of the next internal event after each state transition.

The definition of a coupled model for PDEVS is the same as for Classic DEVS except for the absence of the *select* function (Zeigler et.al. 2000):
$CM = (d_n, X, Y, D, \{ M_d \}, EIC, EOC, IC)$

The execution of a PDEVS model is carried out similarly to Classic DEVS with some changed details in the message handling (Zeigler et.al. 2000).

3.3. Dynamic Structure DEVS

Several approaches extend the Classic DEVS to Dynamic Structure DEVS (DSDEVS). Barros (Barros 1996) and Pawletta (Pawletta et.al. 1996) introduce two DSDEVS variants with an extension of the coupled model definition while the atomic model definition remains unchanged. With theses extensions the coupled model is able to change its structure during simulation time. Uhrmacher (Uhrmacher et.al. 1994) introduces an agent based approach. It defines extensions for both atomic and coupled systems. Another approach is Cell-DEVS, a combination of cellular automata with the DEVS formalism where each cell consist of a single DEVS model (Wainer 2001).

The different types of extensions are carried out due to different application fields or problem definitions e.g. a typical Cell-DEVS application field is social and environmental modeling and simulation. The approaches of Barros and Pawletta are extending the classic formalism without changing its overall principle and thus without changing the general application field of Classic DEVS. The DSDEVS approach of Pawletta enables several options to specify structural dynamics:

- Creation, destruction, cloning and replacement of sub components
- Exchange of a sub component between two coupled models
- Changing coupling definitions of a coupled system

The DSDEVS approach extends the coupled model definition but the atomic model definition stays unchanged. During the simulation time a coupled model can change its structure. Each structure can be seen as a structure state s_i with $s_0, s_1, ..., s_n \in S_{DS}$. A structure state s_i describes all structure relevant elements of a coupled model. Additionally a structural state set H_{DS} can store further structure information e.g. the number of structure changes at the present time or the current structure number. External or internal events, handled by the additional state transition functions $\delta_{x\&s}$ and δ_{int} at coupled model level, induce structure state changes and as a result model structure changes. This dynamic structure extension of Classic DEVS was developed with a regard to hybrid systems, i.e. systems with continuous and discrete event dynamic. In the following only the relevant aspect for discrete event systems are taken into account.

A DSDEVS coupled model is defined by the following 6-tuple (Pawletta et.al. 1996):
$CM_{DS} = (d_{ds}, S_{DS}, \delta_{x\&s}, \delta_{int}, \lambda, ta)$

- d_{ds} specifies the name of the coupled model.
- According to the above definition of a coupled model, its structure consists of sets of sub components and coupling relations. Structure changes mean modifications of these sets. Obviously, the sets of sub systems and coupling relations could be interpreted as a structure state. The set of sequential structure states $\{s_0, s_1, ..., s_n\} = S_{DS}$ defines all structure variants of the variable structure coupled model CM_{DS}. Structure state changes can be induced by handling external or internal events of the coupled model itself or by state events i.e. output events of subordinated components. A structure state is defined by a 9-tuple:
  $s_i = (X, Y, H_{DS}, D, \{ M_d \}, EIC, EOC, IC, select)$
  - *X* and *Y* specify the sets of discrete input and output events. The sets exactly match the sets *X* and *Y* in Classic DEVS. As an extension of DSDEVS the coupled model can directly handle external input events and can create external output events itself.
  - The set H_{DS} represents additional structure related state variables. They are equivalent to the state variable set *S* of an atomic model.
  - *D* specifies the set of sub component names.
  - $M_d \mid d \in D$
    M_d is the model of the sub component *d* of the coupled model CM_{DS}. The set $\{ M_d \}$ defines all sub components of CM_{DS}.
  - *EIC*, *EOC* and *IC* are the external input, external output and internal couplings.
  - The function *select* prioritizes concurrent internal events of the coupled model itself and its sub components.

- $\delta_{x\&s}$: $Q_{DS} \times X \rightarrow H_{DS}$ where $Q_{DS} = \{(h,e) \mid h \in H_{DS}, 0<e<t_{next}\}$
  The external and state transition function $\delta_{x\&s}$ handles external input events and state events i.e. output events of sub components. However it is unreasonable to make changes in the set of sub components or the coupling relations by this function directly. This could lead to ambiguous event handling because external events could simultaneously influence the dynamic of sub components and the structure state. Consequently the $\delta_{x\&s}$ function is only allowed to modify structure related state variables in the set H_{DS}.
- δ_{int}: $S_{DS} \rightarrow S_{DS}$
  The internal transition function δ_{int} changes the structure state s_i to s_{i+1} and as a result induces a structure change of CM_{DS}. The execution of output function λ and internal transition function δ_{int} is

induced by a time driven internal event.

- $\lambda: S_{DS} \rightarrow Y$
  The output function λ generates output events depending on the state S_{DS}.
- $ta: S_{DS} \rightarrow \Re_0^+ \cup \infty$
  As with the dynamic of atomic models, internal events are scheduled by the time advance function *ta.* After each state transition the next internal event is established by the time advance function.

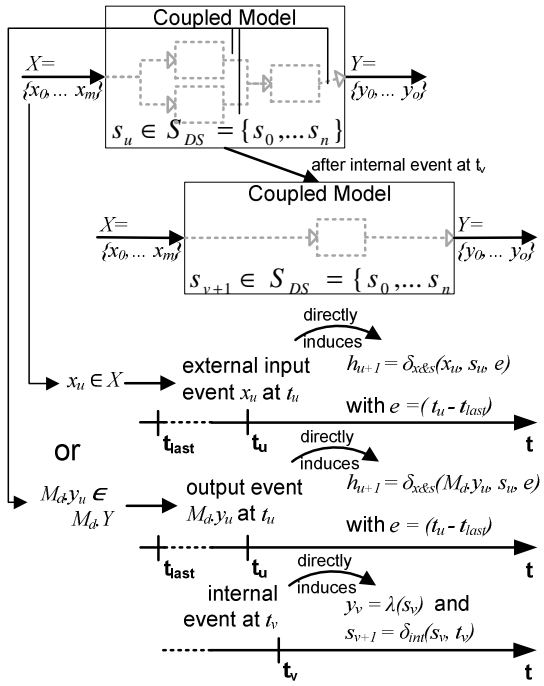


Fig. 4 Dynamic Behavior of a DSDEVS Coupled Model

The dynamic behavior of an atomic model is identical to the behavior in Classic DEVS. Figure 4 shows the dynamic behavior of a dynamic structure coupled model. The figure depicts two external input events and one internal event. Reasons for an input event handling can be an external input event at the input port of the coupled model itself or an external output event at the output port of a sub component M_d of the coupled model. The handling of both events by the coupled model is identically. As a result of an event the structure related state variable set H_{DS} can be changed and with the concluding call of the time advance function an immediate internal event can be induced. An internal event is handled by a coupled model similar to the internal event handling of an atomic model, i.e. the event handling can induce a change of the state sets S and S_{DS}, respectively.

4. EXTENDED DYNAMIC STRUCTURE DEVS

Chapters 3 and 4 introduce the Classic DEVS formalism and several DEVS extensions. This work aims to bring together all introduced approaches and to combine their advantages and application fields. In (Zeigler et.al. 2000) a first step into this direction is undertaken, the introduced PDEVS formalism is a combination of the original PDEVS and DEVS with Ports. The Extended Dynamic Structure DEVS (EDSDEVS), proposed here, combines the extensions: Classic DEVS with PDEVS, DSDEVS and DEVS with Ports. The selection of the extensions is carried out to ensure the preservation of the generic modeling and simulation principles of Classic DEVS. The fusion results in a DEVS formalism with the following main characteristics:

- Modular, hierarchical and dynamic structure modeling and simulation formalism,
- Formal description by sets and functions,
- Exact definition of simulation algorithms,
- Dynamic behavior description in atomic models,
- Dynamic structure description in coupled models,
- Exact behavior definition of concurrent events,
- Substantial similarity between real system and model.

The next sections focus on the formal concept of EDSDEVS modeling with formal descriptions, dynamic behavior descriptions and introduction of the simulation concept with abstract simulator algorithms.

4.1. Formal Concept

The EDSDEV formal descriptions of coupled and atomic models as a combination of sets and functions are structured similar to the Classic DEVS formal description. The EDSDEV atomic model am_{EDS} is defined as an 8- tuple:

$am_{EDS} = (X, Y, S, \delta_{ext}, \delta_{int}, \delta_{con}, \lambda, ta)$

- $X = \{(p,v) \mid p \in \text{InputPorts}, v \in X_p\}$
  $Y = \{(p,v) \mid p \in \text{OutputPorts}, v \in Y_p\}$
  The definitions of both sets are identical to the definitions in DEVS with Ports.
- S specifies the internal states set and is identical to set S of a Classic DEVS atomic model.
- $\delta_{ext}: Q \times X^b \rightarrow S$ with $X^b = \{x_i \mid x_i = (p,v),\ p \in \text{InputPorts},\ v \in X_p\}$ and $Q = \{(s,e) \mid s \in S,\ 0 < e < t_{next}\}$
  The external state transition function δ_{ext} handles a bag covering external inputs. Each input consists of a pair of a discrete input $v \in X_p$ and an input port $p \in \text{InputPorts}$. The set X_P is the set of discrete inputs at port p and *InputPorts* is the set of input ports of model am_{EDS}. The function δ_{ext} can induce an internal event with a rescheduling of the time of the next internal event. This extended definition of δ_{ext} is a fusion of the δ_{ext} definitions of PDEVS and DEVS with Port.
- $\delta_{int}: S \rightarrow S$
  The internal state transition function δ_{int} can establish a new internal state. The execution of output function λ and internal state transition function δ_{int} is induced by a time driven internal event. The time of an internal event is established by the time advance function *ta*. The definition is identical to the definition in Classic DEVS.
- $\delta_{con}: S \times X^b \rightarrow S$
  The confluent transition function δ_{con} handles the

execution order of δ_{int} and δ_{ext} functions during concurrent external and internal events. In spite of the same function signature $\delta_{con}(s, X^b)$ the parameter X^b is different to that in the PDEVS definition as described in section 3.2. Anyhow the three δ_{con} definitions from there also apply here. This extended definition of δ_{con} is based on the PDEVS δ_{con} function definition. Unlike in PDEVS the function has to handle a bag covering inputs, each consisting of a discrete input, input port pair.

- λ: $S \rightarrow Y^b$ whit $Y^b = \{y_i \mid y_i = (p, v), \quad p \in OutputPorts, v \in Y_p\}$
  The output function λ can generate a bag covering outputs Y^b. In spite of the same function signature $Y^b = \lambda(s)$ the function result Y^b is different to that in the PDEVS definition as described in section 3.2. The function result is a bag covering outputs $Y^b=\{ y_i \mid y_i = (p, v) \}$ each consisting of a pair of discrete output $v \in Y_p$ and output port $p \in OutputPorts$. The set Y_P is the set of discrete outputs at port p and *OutputPorts* is the set of output ports of model *am*. If and which outputs are generated depends on the internal state *S*. This extended definition of λ is based on the PDEVS λ function definition. Unlike in PDEVS the function generates a bag covering outputs each consisting of discrete output and output port pairs as introduced in DEVS with Ports.
- *ta*: $S \rightarrow \Re_0^+ \cup \infty$
  The time advance function *ta* schedules the time of the next internal event after each state transition. The definition is identical to Classic DEVS.

Figure 5 shows the dynamic behavior of an atomic EDSDEVS model am_{EDS}.

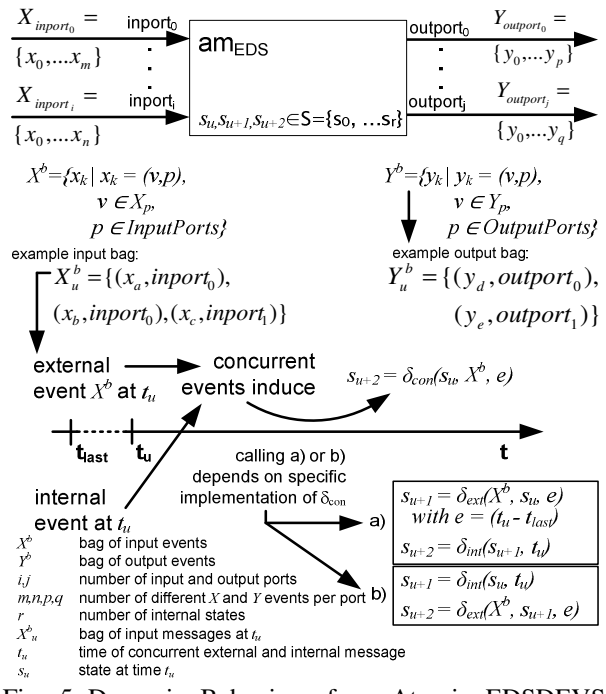


Fig. 5 Dynamic Behavior of an Atomic EDSDEVS Model

At time t_u the confluent transition function δ_{con} handles two concurrent events. The first event contains a bag covering external inputs received by the atomic model am_{EDS}. The figure depicts an example bag covering three external inputs received at two different input ports. A concurrent internal event at t_u was scheduled by the previous execution of the time advance function *ta*. Depending on the specific implementation of function δ_{con} sequence a) or b) is executed. The execution of λ creates a bag covering outputs. The shown bag Y_u^b covers two outputs.

An Extended Dynamic Structure DEVS coupled model is defined by the following 7-tuple:

$CM_{EDS} = (d_n, S_{EDS}, \delta_{x\&s}, \delta_{int}, \delta_{con}, \lambda, ta)$

- d_n specifies the name of the coupled model.
- In the EDSDEVS formalism the coupled model structure consists not only of sets of sub components and coupling relations as in DSDEVS but also of additional interface definitions i.e. input and output port definitions. The set of sequential structure states $\{s_0, s_1, ...,s_n\} = S_{EDS}$ has to define all structure variants of the coupled model CM_{EDS}. Two model structure variants can vary in different interface definitions, in contrast to DSDEVS where each model has a non-variable interface with a single input and a single output port. Hence, a structure state has to incorporate interface definitions with sets of input and output ports additionally to the structure state definition as introduced in section 3.3. An EDSDEVS structure state is defined by a 10-tuple:
  $s_i = (X, Y, H_{EDS}, D, \{ M_d \}, InputPorts, OutputPorts, EIC, EOC, IC)$
  - *X* and *Y* specify the sets of discrete input and outputs. The sets exactly match the extended definitions of *X* and *Y* as introduced in DEVS with Ports.
  - The sets H_{EDS}, *D* and M_d exactly match the sets H_{VS}, *D* and M_d of the DSDEVS formalism introduced in section 3.3.
  - *InputPorts* and *OutputPorts* specify the sets of input and output port names of the coupled model CM_{EDS}. These two elements of the structure state s_i are introduced by the EDSDEVS formalism.
  - *EIC*, *EOC* and *IC* are the external input, external output and internal couplings of CM_{EDS}. The definition of the coupling relations exactly match the definition as introduced with the DEVS with Ports extension.

- $\delta_{x\&s}$: $Q \times X^b \rightarrow H_{EDS}$ where X^b is a bag covering input, input port pairs and $Q = \{(h,e) \mid h \in H_{EDS}, 0<e<t_{next}\}$
  The external and state transition function δ_{ext} handles a bag covering inputs, each consisting of a pair of a), b) or c):
  a) A discrete input $v \in X_p$ and an input port $p \in InputPorts$. The set X_P is the set of discrete

inputs at port p and *InputPorts* is the set of input ports of model CM_{EDS}.

b) A discrete output $v \in M_d.Y_p$ and an output port $p \in M_d.OutputPorts$ where M_d is the model of the sub component d of the coupled model CM_{EDS}. The set $M_d.Y_P$ is the set of discrete outputs at port p and $M_d.OutputPorts$ is the set of output ports of model M_d.

c) A discrete input $v \in M_d.X_p$ and an input port $p \in M_d.InputPorts$ where M_d is the model of the sub component d of the coupled model CM_{EDS}. The set $M_d.X_P$ is the set of discrete inputs at port p and $M_d.InputPorts$ is the set of input ports of model M_d.

This extended definition of δ_{ext} is a fusion and extension of the δ_{ext} definitions of DSDEVS, PDEVS and DEVS with Ports. In DSDEVS only state events induced by output events of sub components are handled. However, an output port can have coupling relations to multiple input ports. In this case there is a difference in the handling of a single output event of a single source sub model or multiple input events of different destination sub models. Hence, the external and state transition function of EDSDEVS can handle both output and input events. However, the functionality is in accordance with the description of the DSDEVS external and state transition function $\delta_{x\&s}$.

- δ_{int}: $S_{EDS} \rightarrow S_{EDS}$
  ta: $S_N \rightarrow \Re_0^+ \cup \infty$
  The internal state transition function δ_{int}, and the time advance function ta exactly match the functions of the DSDEVS formalism.
- δ_{con}: $S_{EDS} \times X^b \rightarrow S_{EDS}$
  The confluent transition function δ_{con} handles the execution sequence of δ_{int} and δ_{ext} functions during concurrent external and internal events. The EDSDEVS formalism introduces the confluent transition function also at coupled model level due to the fusion of PDEVS and DSDEVS. An EDSDEVS coupled model handles external, state and internal events. Hence and in contrast to PDEVS, in EDSDEVS concurrent external and internal events can occur also at coupled model level. Consequently, a confluent transition function to handle concurrent events is necessary at this level. The functionality is in accordance with the description of the confluent transition function δ_{con} at atomic model level in this section.
- λ: $S_{EDS} \rightarrow Y^b$
  The output function λ generates a bag covering outputs $Y^b = \{y_i\}$ depending on state S_{EDS}. An output y_i consists of a pair of discrete output $v \in Y_p$ and output port $p \in OutputPorts$. The set Y_P is the set of discrete outputs at port p and *OutputPorts* is the set of output ports of model CM_{EDS}. The output function λ in the EDSDEVS formalism merges three sources:
  - The output function λ at coupled model level is introduced by DSDEVS.
  - The definition of the function creating a bag covering outputs is based on PDEVS.
  - The output event structure with pairs of output/output port is introduced by DEVS with Ports.

Figure 6 shows the dynamic behavior of a coupled EDSDEVS model CM_{EDS}. At time t_u the confluent transition function δ_{con} handles concurrent external and internal events. The first event is a bag covering inputs received at input ports by the coupled model CM_{EDS}. A concurrent internal event at t_u was scheduled by the last execution of the time advance function. Depending on the specific implementation of function δ_{con} sequence a) or sequence b) is executed. The execution of the internal state transition function δ_{int} can change the structure state s_u to s_{u+1} or s_{u+1} to s_{u+2} and therefore the model structure of CM_{EDS} to CM^*_{EDS}. The execution of the output function λ creates a bag covering outputs Y_u^b. The depicted example bag Y_u^b covers two outputs.

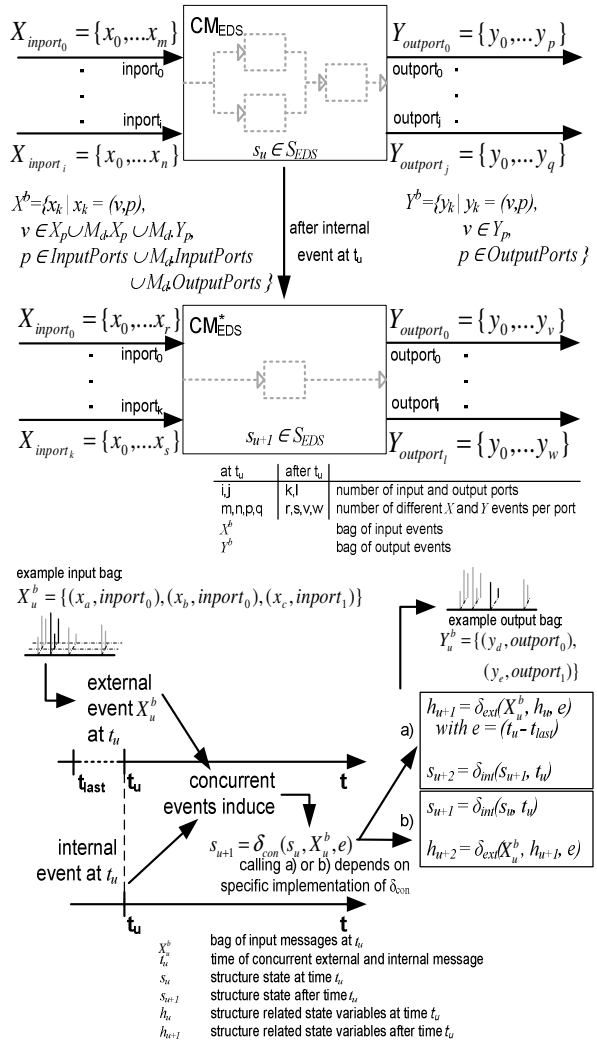


Fig. 6 Dynamic Behavior of a Coupled EDSDEVS Model

4.2. EDSDEVS Simulation

The simulation engine for EDSDEVS models is a combination and extension of the simulation algorithms of Classic DEVS, PDEVS and DSDEVS. The message handling of coordinators are largely similar to simulators. Each coordinator holds its own time of next internal event in t_{next_c} and searches the minimum time of next internal event in t_{next} of sub components and in its own t_{next_c}.

Figure 7 depicts an EDSDEVS model example with associated simulation model elements i.e. root coordinator, coordinator and simulator instances, message handling and model function calls. The overall structure is very similar to the Classic DEVS simulation model execution except for additions at the coordinators and associated coupled models. Because of complexity and clarity selected situations are shown in sections:

i. (Figure 7a) initialisation phase with i-message handling:
   During the initialisation phase model component's init functions are called because of an i-message handling similar to Classic DEVS. Additionally, after structure changes during the simulation phase the init function is called too.

ii. (Figure 7b) *-message handling created due to an internal event of model *am2*:
   The root coordinator advances the simulation clock and a *-message is firstly created. The message is sent to the successor coordinator instance of coupled model *CM1* (not depicted). This coordinator instance compares the actual simulation time t with its own next internal event time stored in t_{next_c} and determines that it is not responsible for handling this event. Hence, the event is forwarded to the successor coordinator instance of *CM2*. The coordinator instance is again not responsible for handling the message itself but knows that a sub component scheduled the event. The coordinator instance will then forward the message to the appropriate simulator instance associated with *am2*. The simulator instance of *am2* calls the model functions λ and δ_{int}. A result of calling λ could be a y-message sent back to the subordinate coodinator instance of *CM2*. This coordinator instance reacts with the call of the model function $\delta_{x\&s}$ of *CM2* and a message forward to the simulator instance of *am3* due to an appropriate IC coupling.

iii. (Figure 7c) *-message handling created due to an internal event of model *CM2*:
   The depicted situation is similar to 7b except that the coordinator instance of *CM2* determines that simulation time t and its t_{next_c} are equal. Hence, it has to handle the *-message itself with calling λ and δ_{int} model functions of *CM2* with the possibility of generating a y-message sent to a sub component and/or superordinated coordinator instance and of changing its sequential structure state S_{EDS}.

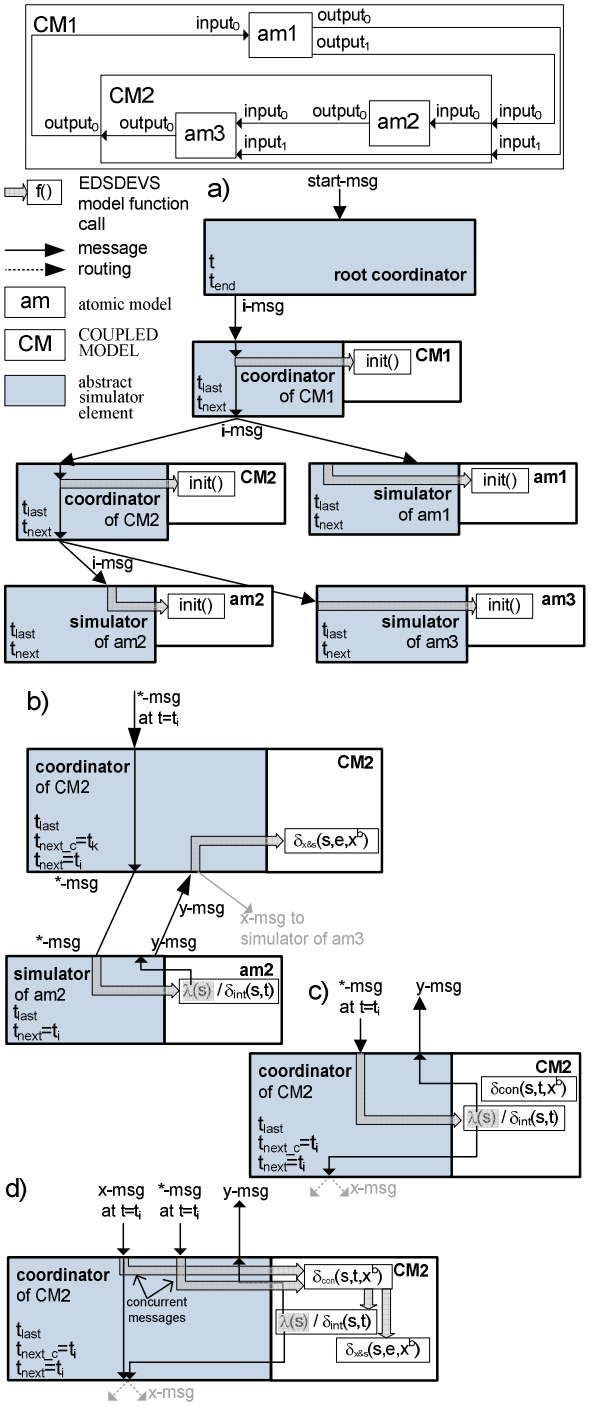


Fig. 7 EDSDEVS Model Example with Simulation Model Elements and Message Flow during Initialization and Simulation Phases

iv. (Figure 7d) concurrent event handling with the confluent transition function δ_{con}:
   The figure depicts the handling of concurrent external and internal messages by the coordinator instance of *CM2*. The confluent function of *CM2* is called to handle the concurrent messages. Depending on the specific implementation of δ_{con} the external transition function $\delta_{x\&s}$ and internal transition/output functions δ_{int}, respectively, are firstly called. The external message is concurrently

handled by the function δ_{con} and forwarded to the simulator instance of sub component *am2* as an x-message due to an appropriate EIC. Calling the output function λ could cause an y-message sent to a sub component and/or superordinated coordinator instance.

Listings 1 and 2 show the pseudo codes of the EDSDEVS simulator components.

```
variables:
    t_last   // time of last event
    t_next   // time of next int state event
    am       // associated atomic model

// t=0 init at simulation start
// t>0 init after structure change
when receive i-msg(t)at time t
    am.init(t)
    t_last := t
    t_next := am.ta()

when receive *-msg(t) at time t
    if t <> t_next
       error: bad synchronisation
    y_bag := am.λ()
    send y_bag in a y-msg to parent coord.

when receive x-msg(t, x_bag) at time t
 with value x_bag containing x.value und
 x.port pairs
    if not (t_last ≤ t ≤ t_next)
       error: bad synchronisation
    if t=t_next and x_bag is not empty
       //concurrent ext. & int. event
       am.δ_con( t, x_bag)
    else if t=t_next and x_bag is empty
       // internal event
       am.δ_int(t)
    else
       // external event
       am.δ_ext( t-t_last, x_bag)
    end if
    t_last := t
    t_next := t_last + am.ta()
```

Listing 1 Pseudo Code of an EDSDEVS Simulator

```
variables:
    t_last   // time of last event
    t_next   // minimal time of next int.
             // state event of coupled model
             // or sub component
    t_next_c // time of next int state event
             //of the coupled model itself
    CM       // associated coupled model with
             // CM.s_t current structure state
    IMM      // imminent children
    mail     // output mail bag

// t=0 init at simulation start
// t>0 init after structure change
when receive i-msg(t)at time t
    CM.init(t)
    foreach sub component M_d ∈ CM.s_t.M
       send i-msg(t) to M_d
    t_last := t
    // determine time of next scheduled
    // internal state event of coupled
    // model itself
    t_next_c := CM.ta()
    // determine minimum time of next
    // scheduled internal state events of
    // coupled model and all subcomponents
    t_next := min( t_next_c, { M_d.t_next | M_d
      ∈ CM.s_t.M } )

when receive *-msg(t) at time t
    if t <> t_next & t<>t_next_c
       error: bad synchronisation
    // internal state event of CM
    if t=t_next_c
       y_bag := CM.λ()
       send bag of value/output port pairs
        in a y-msg to parent coordinator
    // internal state event of a subcomp.
    else if t=t_next
       // find all subcomps with t_next==t
       IMM:={M_d |M_d ∈ CM.s_t.M ∧ M_d.t_next= t}
       foreach M_d in IMM
          send *-msg(t) to M_d

when receive x-msg(t, x_bag) at time t
 with x_bag containing x.value/x.port
 pairs
    if not (t_last ≤ t ≤ t_next_c)
       error: bad synchronisation
    if t=t_next_c and x_bag is not empty
       // concurrent ext. and int. event
       CM.δ_con( t, x_bag)
    else if t=t_next_c and x_bag is empty
       CM.δ_int( t )  // int. event
    else
       CM.δ_x&s( t-t_last, x_bag) //ext. event
    end if
    // get all subcomponents M_d* with an
    // appropriate EIC
    receivers:=subcomponents{M_d|M_d∈CM.s_t.M}
     with {coupling|coupling∈CM.s_t.EIC}
    // forwards x-msg to all appropriate
    // subcomponents
    foreach subcomponent M_d* in receivers
       // ext. event of subcomponent
       CM.δ_x&s( t-t_last, x_bag)
       send x-msg(t, x_bag, M_d*.p) to M_d*
        at port p
    foreach subcomponent M_d* in IMM and not
     in receivers
       // send empty bag without inputport
       send x-msg(t, NULL, NULL) to M_d*
    t_last := t
    t_next_c := t_last + CM.ta()
    t_next := min(t_next_c,{M_d.t_next|M_d∈CM.s_t.M})

when receive y-msg(t, y_bag, d) at time t
with y_bag with value/port pairs from d
    // collect all y-msgs from all subcomp
    if d is not the last not reporting d
     in IMM
       add (y_bag, d) to mail
       mark d in IMM as reporting
    // all subcomps now handled their *msg
```

```
else if d is the last not reporting d
 in IMM
    CM.δ_x&s(t-t_last, mail)
    // check ext. coupling to form sub-
    // bag of parent output
    y_bag_parent = NULL
    foreach d in mail where (y_bag and
     d) has an appropriate EIC
        add y_bag to y_bag_parent
    send y-msg(t, y_bag_parent,, CM) to
     parent model
    // check IC to get children M_d*
    // with an appropriate IC who
    // receives a sub bag
    receivers := subcomponents{M_d|d in
        mail, M_d∈CM.s_t.M} with
        {coupling|coupling∈CM.s_t.IC}
    foreach subcomp M_d* in receivers
        creates sub bag x_bag from mail
         with elements where M_d* is
         receiver
        send x-msg(t, x_bag) to M_d*
        mark d in IMM as sending
    foreach sub component M_d* in IMM
     where M_d* is not sending
        send x-msg(t, NULL) to M_d*
t_last := t
t_next_c := t_last + CM.ta()
t_next := min( t_next_c, { M_d.t_next | M_d
 ∈ CM.s_t.M } )
```

Listing 2 Pseudo Code of an EDSDEVS Coordinator

5. CONCLUSIONS

The EDSDEVS formalism introduced in this contribution is a fusion of Classic DEVS with several extensions. This approach is an as generic as possible modeling and simulation formalism based on DEVS. It widens significantly the application area of DEVS modeling and simulation. Further extensions are desirable and essential. To establish a widely accepted modeling and simulation approach extensions for parallel computing and graphical modeling are necessary. There are also approaches for hybrid DEVS extensions i.e. the support of continuous state changes. These proposals are recommended as further research.

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A Framework for Simulation Based Structure and Parameter Optimization of Discrete Event Systems

Olaf Hagendorf, Thorsten Pawletta

Simulation with integrated parameter optimization of a given model structure is a well established technique today. However, with increasing system complexity and flexibility the number of possible structure variants increases. Therefore the potential benefit of automatic model structure optimization becomes significant. During optimization, the introduced framework supports automatic parameter variation in concert with a re-configuration of model structure. This is achieved by means of a combination of optimization, simulation, and model management methods. Using this approach simulation is employed to determine the performance of a current model structure and its parameters. An optimization method searches for an optimal solution with repeated, simultaneous model structure and model parameter changes. The model structure changes are assisted by a model management method.

1 Introduction

Research and application of simulation based optimization has seen a significant development in recent years. A Google search on 'Simulation Optimization' in 2006 found ca. 4.000 entries [1] in comparison to a search in 2008 that found almost 80.000 entries with among the results articles, conference presentations, books, and software.

Till relatively recently, the simulation community was resistant to the use of optimization tools. Optimization models seem to over-simplify the real problem and it was not always clear

why a certain solution was the best [5]. The situation changed at the end of the 90s. An ACM Digital Library [23] search on 'Simulation Optimization' found 16.000 articles between 1960 and 2008. A significant number (15500) of articles has been published during the last 20 years and only 500 articles in the 28 years before. Two reasons for this change may be the advances in modeling and simulation methods and increase of computing power over the past two decades that has enabled simulation based optimization. Currently there are several algorithms to change simulation model parameters to establish solutions with good performance and methods to compare different solutions in terms of quality. Many commercially available discrete event or Monte Carlo simulation software packages contain optimization methods to search for optimal input and system parameter values. Several such packages are described in [2].

This chapter addresses a fundamental problem of simulation based optimization: The technique is well established but is restricted to the optimization of system parameters. In using this established technique, the model structure is considered to be fixed as the structure of model elements is defined during model development before an optimization experiment. As model performance is optimized it may be necessary to redesign the model structure. This would conventionally be done manually by an analyst using previous simulation results, observations, or decisions based on previous experience. With increasingly complex, highly flexible, and dynamic structure models, the number of possible structure variants increases and the potential benefit of automatic model structure optimization would be significant.

The focus of this chapter is the description of a methodology for a simulation based parameter and structure optimization for modular, hierarchical discrete event systems. In contrast to current approaches that use modeling and simulation, here the model structure is variable and thus it is open to optimization. The variation of model structure and model parameters is

controlled by a super ordinate optimization module. The introduced simulation based optimization framework consists of three main elements: (i) model management, (ii) modeling and simulation, and (iii) optimization.

i. As a basis for the model management method the System Entity Structure/Model Base (SES/MB) approach, introduced by Rozenblit, Zeigler *et al.* [20][27][28] is employed. The SES/MB approach is a generative, knowledge base framework consisting of a tree like system entity structure and a model base containing basic components. It supports the definition of a set of modular, hierarchical models and the generation of specific model structures using predefined basic components from a model base. Because of this characteristic a modular, hierarchical modeling and simulation method has to be employed.

ii. The modeling and simulation approach based on the Discrete Event System Specification (DEVS) formalism introduced by Zeigler [26][27] is an established method in the field of modular, hierarchical modeling and simulation. Dynamic Structure DEVS (DSDEVS) as an extension of DEVS offers methods to allow structural changes during a simulation run [6][15][25][27]. In countless applications, for example in [8][9], the advantages of a dynamic structure modeling and simulation method are considerable. A DSDEVS method based on work in [9][15][16] is integrated in the novel simulation based optimization approach. However, detailed aspects of DSDEVS systems are not considered in this chapter.

iii. The optimization method controls the variation of model parameters and structure. Genetic algorithms have delivered robust solutions for various simulation based optimization problems, for example in [17][18][24]. The genetic algorithm documented in [24] will be employed as optimization method in the framework.

Section 2 provides a short preview of conventional simulation based optimization aspects and

introduces the fundamentals of a combined structure and parameter optimization approach. Section 3 briefly describes the applied SES/MB approach as a model set organization and model generating meta-modeling method with necessary changes of the original approach. The synthesis of the three fundamental methods, optimization, model management, and modeling and simulation to perform a simulation based structure and parameter optimization is presented in Section 4. Finally, the usage of the new optimization approach is demonstrated by an industrial application in Section 5.

2 Simulation based Optimization

For all its achievements, a disadvantage of modeling and simulation is the missing optimization capability. For many years simulation experiments, as shown in figure 2.1, have been state of the art. An analyst creates a model, for example based on a real system, transforms the model to an

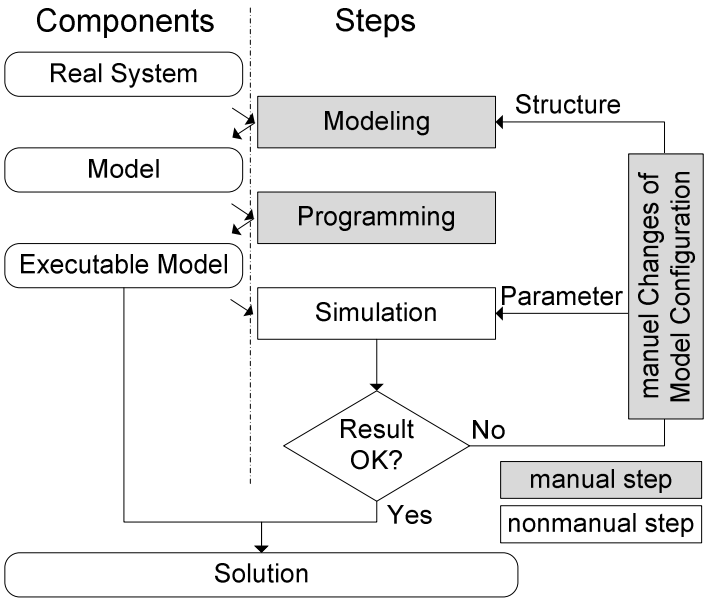

Figure 2.1 An example of a conventional simulation experiment

executable model and executes a simulation with it. After a review of simulation results, if necessary, the model configuration, that is, model parameters and/or model structures, has to be

manually changed by an analyst. Using a manual procedure only a relatively small number of system configurations can be examined until a suitable solution is chosen.

Through the combination of modeling and simulation with optimization methods a simulation based optimization approach is achieved that can reduce the effort of this manual procedure. Mathematical optimization generally means establishing a function minimum or maximum. Simulation based optimization means finding the best model configuration by minimizing a function of output variables estimated with a simulation method [21].

2.1 Parameter Optimization

An established approach of a simulation based optimization is simulation based parameter optimization. The overall goal of this optimization approach is the identification of improved settings of user selected model parameters under control of performance measures. There is an extensive and varied body of literature on this topic that includes several tutorials, reviews, and summaries of the current state of the art (e.g., [3][4][7][14][21][22]). Law and Kelton describe in [11] commercially available simulation tools with integrated optimization techniques using this approach of simulation based parameter optimization. Figure 2.2 shows a principle example of a simulation based parameter optimization experiment. The procedure to create an executable model follows the procedure described in Fig. 2.1. A crucial difference is the detachment of model and model parameters. Based on this detachment the optimization method is able to alter model parameters to minimize the result of an objective function. The objective function measures the model performance with current model parameters. In most instances improving the model performance means minimizing the objective function result. Model parameter adjustments are carried out in a loop until a stop criterion is fulfilled. Examples of stop criteria are (i) going below a minimum alteration rate of objective function result or (ii) exceeding the

maximum number of optimization cycles. The result of a successful optimization experiment is a parameter optimized model.

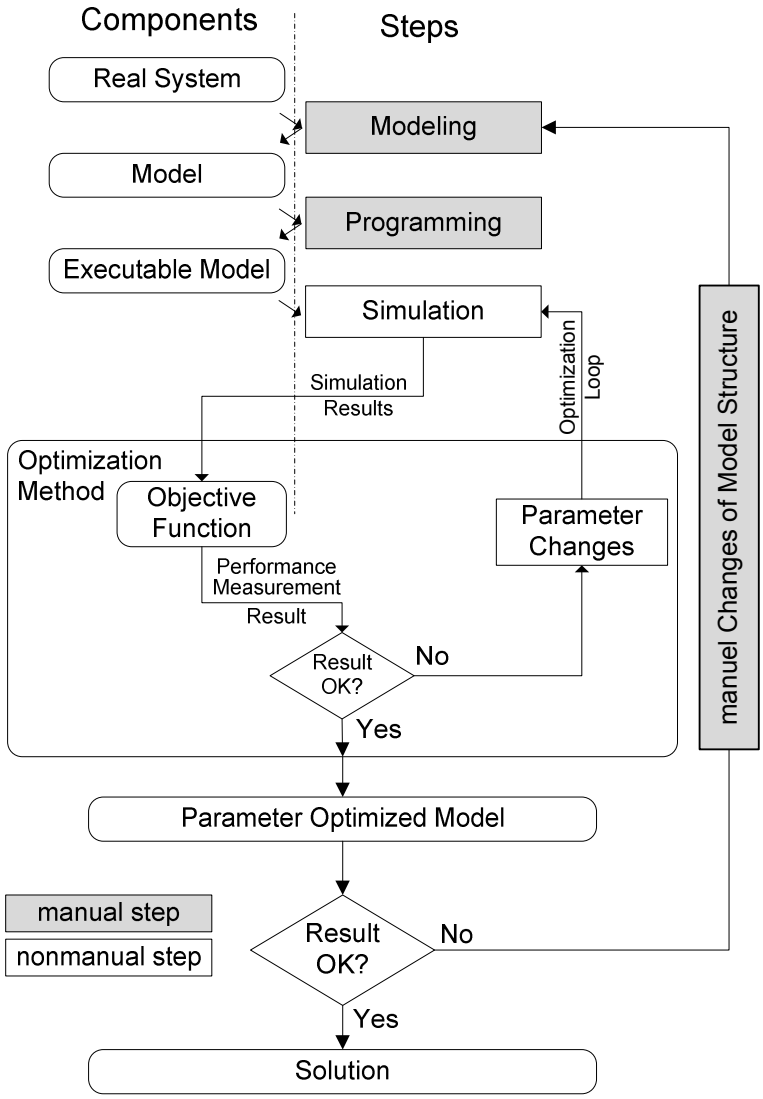

Figure 2.2 An example of a simulation based parameter optimization experiment

According to [21], a simulation based parameter optimization problem O with a set of m model parameters $X = \{x_1, \ldots x_m\}$ can be described as follows:

- A parameter set $X = \{x_1, \ldots x_m\}$ has the domain set $D = \{d_1 \ldots d_m\}$.
- The multi-dimensional (one for each parameter) search space S is defined by

$S = \{s = \{(x_1,v_1) \ldots (x_m,v_m)\} \mid v_i \in d_i\}$.

- A set Y is the output set defined by $Y = \{y_1 \ldots y_n\} = Y(X)$ and estimated by simulation. Simulation experiments are often based on stochastic parameters and properties. Hence the output set Y is stochastic too.
- The objective function F establishes a single stochastic value from output set $Y : F = F(Y) \rightarrow \Re+$. The result of the objective function is a measure of the current model performance.
- Because of the stochastic nature of Y and consequently of F. an estimation function R, the simulation response function defined by $R(X)=E(F(Y(X)))$, is optimized, that is, in the scope of this approach it is minimized.
- Depending on the optimization problem and analysis required, the exchange of the last two steps, evaluation of objective function F and simulation response function R, can save computational effort. Hence, the simulation response function is defined by $R(X) = E(Y(X))$ and subsequently the objective function by $F(X) = F(R(X))$.

Each parameter set $X_i \in S$ can be seen as a possible solution of O. The optimization method has to search the space S to find the parameter set $X_{opt} \in S$ with $E(F(Y(X_{opt}))) \leq E(F(Y(X))) \ \forall X \in S$. The resulting parameter set X_{opt} is considered the global optimum of O.

This approach is restricted to automated parameter optimization. It is important to note that automatic structure changes during optimization are not possible with this approach. Instead, structure changes are carried out manually by an analyst and each manual structure change requires a repetition of the automated parameter optimization.

2.2 Combined Parameter and Structure Optimization

The extension of the optimization approach with the ability to additionally change model

structure to improve system performance is a development of the idea introduced in Section 2.1. This extension is mainly directed towards a simulation based structure and parameter optimization as presented in Fig. 2.3.

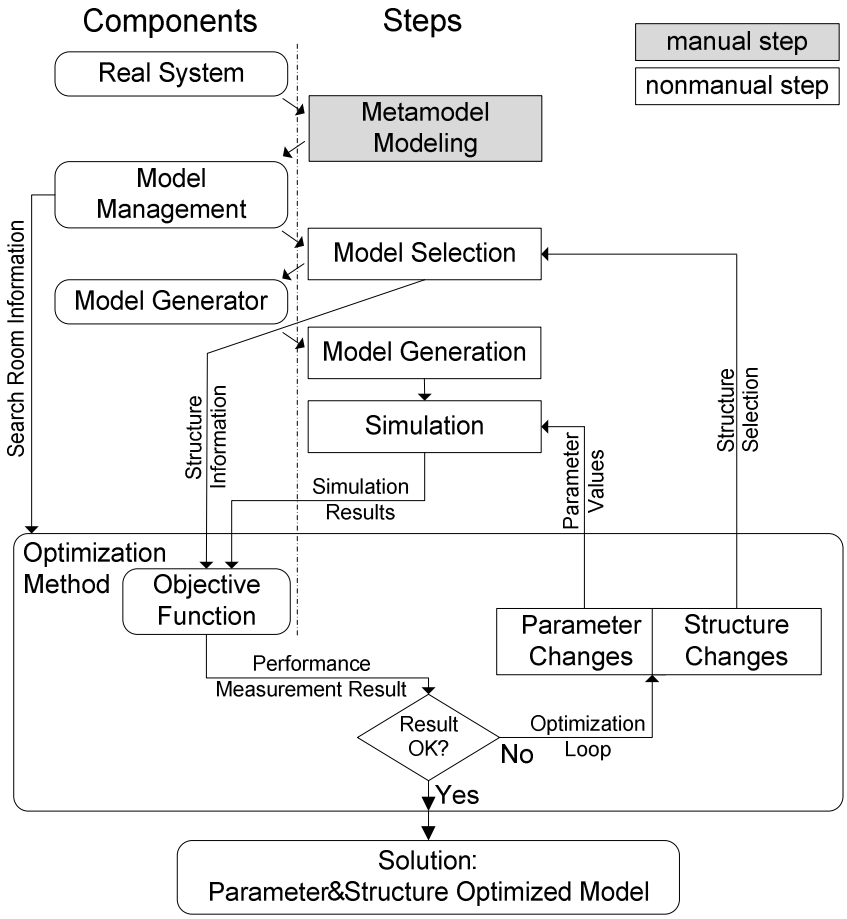

Figure 2.3 Components and steps of a simulation based parameter and structure optimization experiment

The approach of a simulation based parameter and structure optimization differs in the following point from the simulation based parameter optimization described in Section 2.1:

- An analyst does not generate a single model of the real system. In this case he has to organize a set of models. One way of achieving this is to define a model that describes a set of model variants instead of one single model of the system under analysis. Models that define the

creation and interpretation of a set of models are named meta-models. If a model is the abstraction of an aspect of the real world, a meta-model is yet another, super-ordinate abstraction of the model itself. That is, when a model describes the behavior and structure of a real system then a meta-model describes the behavior and structure of different models that all describe the behavior and structure of the same real system in a slightly different way.

- The model management organizes the set of model structures and provides a model selection method.
- The model selection is controlled by an optimization method. The selection method delivers the selected model structure information to a model generator that generates an executable model.
- The objective function receives simulation results and additional information gathered during model selection to estimate the performance of the current model configuration.
- The optimization method investigates the search space with simultaneous model parameter and model structure changes without manual involvement. The intention of the optimization method is the finding of a point in the search space with the optimal objective function result.
- The optimization process is separated into an initialization and an optimization phase:
    1. In the initialization phase, the model management module delivers information about the search space defined by the set of all model configurations to the optimization module.
    2. In the optimization phase, the model management module receives information from the optimization module about the currently investigated point in the search space. This information is used to select a new model structure and to initialize the model parameters.

A prerequisite for an optimization is the definition of a search space. In the approach presented here, the search space is multi-dimensional as a result of the combination of model structure and

model parameter variants. During the optimization loop several points of the search space are examined. Each point defines a model structure with an appropriate parameter set. The extension of the formal description of a simulation based parameter optimization problem O, defined in Section 2.1, to a combined simulation based structure and parameter optimization leads to O^* shown in a schematic diagram in Fig. 2.4:

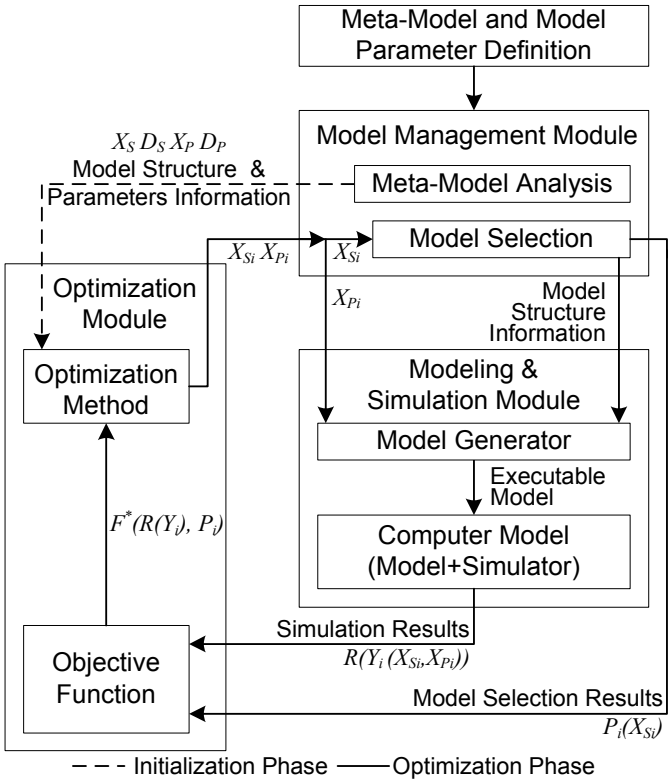

Figure 2.4 Schematic diagram of a simulation based parameter and structure optimization experiment

- The model parameter set X_P and its domain set D_P, in Section 2.1 defined as X and D, are extended by structure parameter set X_S and its domain set D_S. The extended set of definitions are: $X^* = X_P \cup X_S = \{x_{P1} \ldots x_{Pm}, x_{S1} \ldots x_{Sn}\}$ and $D^* = D_P \cup D_S = \{d_{P1} \ldots d_{Pm}, d_{S1} \ldots d_{Sn}\}$ with m model parameters in set X_P and n structure parameters in set X_S. The sets X_P and D_P are defined by the current model. The model management has to provide the sets X_S and D_S

by analyzing the meta-model.

- The multi-dimensional (one for each parameter) search space $S = S_P \cup S_S$ is spanned by sets of model parameter and structure variants.
- The objective function F^* is defined by $F^*(Y(X^*),P(X_S))$ with simulation results $Y(X^*)=Y(X_S \cup X_P)$ and results based on structure related variables $P(X_S)$ that are established during the model selection. Because of the stochastic nature of the simulation results $Y(X^*)$ an estimation function R, the simulation response function, is calculated. The results based on structure related variables $P(X_S)$ are not stochastic. Hence, the simulation response function is defined by $R(Y(X^*))$ and subsequently the objective function by $F^*(R(Y(X^*)), P(X_S))$.

Through the inclusion of a model management method, the optimization method can simultaneously control parameter changes as well as model structure changes to find an optimal system configuration. The model management method takes a crucial role in this approach. The description of a model management method based on meta-modeling follows in the next section.

3 Meta-Modeling – Specification and Organization of Model Sets

Zeigler introduced in [27] a simulation based system design approach. It is a *plan – generation – evaluation* process. The *plan* phase organizes design alternatives with different model structures and model parameters within defined system boundaries to satisfy given design objectives. During the *generation* phase a specific model design is chosen and the corresponding model is generated. This model is simulated during the *evaluation* phase using an experimental frame derived from the design objectives.

The System Entity Structure/Model Base approach (SES/MB) [20][27] is such a

simulation based system design approach. It is specifically configured to define, organize, and generate modular, hierarchical models and was developed to assist an analyst in model organization and generation. To represent a set of modular, hierarchical models, the SES/MB approach is able to describe three relationships: *decomposition*, *taxonomy,* and *coupling*. *Decomposition* means the formalism is able to decompose a system object called 'entity' into sub-entities. *Taxonomy* means the ability to represent several possible variants of an entity called 'specialization'. To interconnect sub-entities the definition of *coupling* relationships are necessary. With these features the SES/MB approach meets the needs of the model management method in the proposed simulation based optimization concept.

Fundamental properties of the SES/MB approach are [20][27]:

- A modular, hierarchical model is constructed based on: (i) the declarative system knowledge coded in a SES and (ii) predefined basic system models stored in a MB.
- The partitioning of a modular, hierarchical model is highly dependent on the design objectives. Model parameters are a typical example. They are not really a part of the model composition structure but nevertheless they can become a part of the system entity structure if they are crucial for describing design alternatives.
- The model generation from a SES/MB is a multistage process. The first step is a graph analysing and pruning process to extract a specific system configuration. Based on this information a modular, hierarchical model is generated.

The SES is represented by a tree structure containing alternative edges starting at decision nodes. With the aid of different edge types and decision nodes a set of different model variants can be defined. To choose a specific design and to create a specific model variant, the SES has to be pruned. The pruning process decides at decision nodes which alternative(s) to choose as a

consequence of specified structure conditions and selection rules. The result of this process is a Pruned Entity Structure (PES) that defines one model variant. A composition tree is derived from a PES. The composition tree contains all necessary information to generate a modular, hierarchical model using predefined basic components from MB. Figure 3.1 shows the principal organization and the transformation process: SES → PES → Composition Tree + MB → Modular, Hierarchical Model.

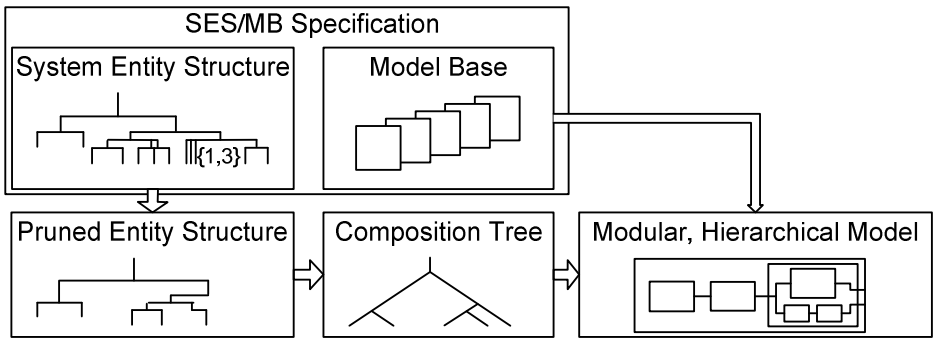

Figure 3.1 SES/MB formalism based model generation

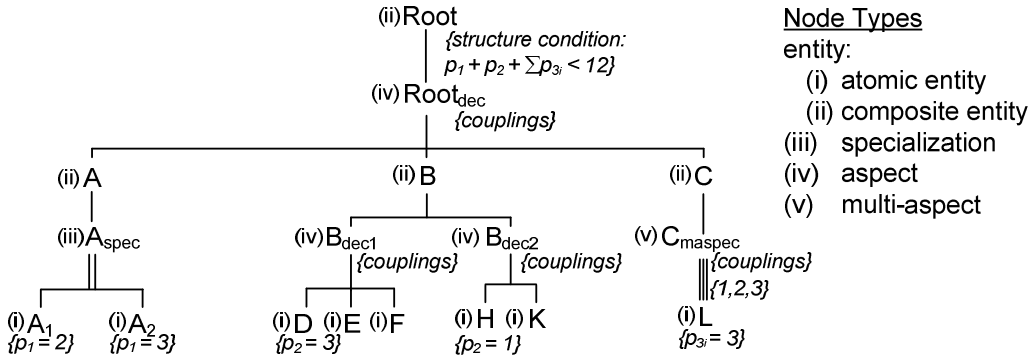

Figure 3.2 An example of a SES

The used SES definition is based on definitions published in [20][27]. Figure 3.2 depicts an example to demonstrate the tree elements. The SES definition differentiates four main types of nodes: *(i & ii) entity, (iii) specialization, (iv) aspect,* and *(v) multi-aspect*. An *entity* node represents a system object. There are two subtypes of *entity* node in fact *(i) atomic entity* and *(ii)*

composite entity. An *atomic entity* cannot be broken down into sub-entities. The model base contains a basic component for each *atomic entity*. A *composite entity* is defined in terms of other entities. Thus, the root node is always of type *composite entity*, while all leaf nodes are always of type *atomic entity*. The root node and each *composite entity* node of the tree have at least one successor node of type *specialization*, *aspect,* or *multiple-aspect*. That means there is an alternate mode between *entity* nodes and other node types. The node type definitions can be briefly summarized:

- *atomic entity node = (name, {av_1,… av_n}}*

  composite entity node = (name, successors, {av_1,… av_n}, structure condition)

  An entity node is defined by a name and is of type *atomic* or *composite*. Both node types may have attached variables *av*. A *composite entity node* can have a single successor node of type *specialization* or *multi-aspect* or multiple successor nodes of type *aspect*. A *composite entity node* can have attached *structure condition.*

- *specialization node = (name, successors)*

  A s*pecialization node* is defined by a name and a set of successor nodes. In the tree it is indicated by a double-line edge. A s*pecialization node* defines the taxonomy of a predecessor entity node and specifies how the entity can be categorized into specialized entities. A s*pecialization node* always has successor nodes of type atomic entity to represent the possible specializations. The s*pecialization node A* in Fig. 3.2 has two specializations defined by the nodes A_1 and A_2.

- *aspect node = (name, successors, coupling specifications)*

  An *aspect node* is defined by a name, a set of successor nodes, and coupling information. It is indicated by a single-line edge in an SES tree. An *aspect node* defines a single possible

decomposition of its parent node and can have multiple successors of type atomic and/or composite entity. The *coupling specification* is a set of couplings and describes how the sub-entities, represented by the successor nodes, have to be connected. Each coupling is defined by a 2-tuple. Each tuple consists of sub-entity source and destination information, for example, (SourceEntity.outputport, DestinationEntity.inputport). The composite entity *B* in Fig. 3.2 has two decomposition variants defined by the *aspect nodes* B_{dec1} and B_{dec2}.

- *multiple aspect node = (name, successor, coupling specification, number range property)*
  The definition of a *multiple aspect node* is similar to an aspect node with an additional *number range property.* It has only one successor node of type atomic entity. It is indicated by a triple-line edge in an SES tree. A *multiple aspect node* also defines a decomposition of a composite entity, but all sub-entities have to be of the same entity type. Only the number of sub-entities is variable according to the attached *number range property*. The *multiple aspect node* C_{maspec} in Fig. 3.2 illustrates the decomposition of composite entity *C* that may be composed by one, two, or three sub-entities *L.*
- *structure conditions* are added to composite entity nodes. They are used as alternative structure knowledge representation instead of selection rules and structure constraints as defined in [20]. A modified pruning process necessitates an alternative representation. During the pruning, sub trees are cut. The remaining s*tructure conditions* are evaluated to verify the PES. Only if all *structure conditions* are true the PES is valid. Figure 3.2 shows an example of a *structure condition* added to composite entity node *ROOT*. If the generated model structure contains the atomic entity nodes A_2*, D, E, F, L,* it would be valid because the condition $p_1+p_2+1*p_3=3+3+1*3<12$ is true.

4 Framework for Modeling, Simulation and Optimization

In this section a complete framework for combined parameter and structure optimization experiments is introduced. After a brief description of the general framework structure, its methods are discussed in detail and finally the entire algorithm is summarized.

4.1 General Framework Structure

Based on the fundamental approach of a parameter and structure optimization experiment in Fig. 2.4, the detailed structure of the introduced framework is depicted in Fig. 4.1.

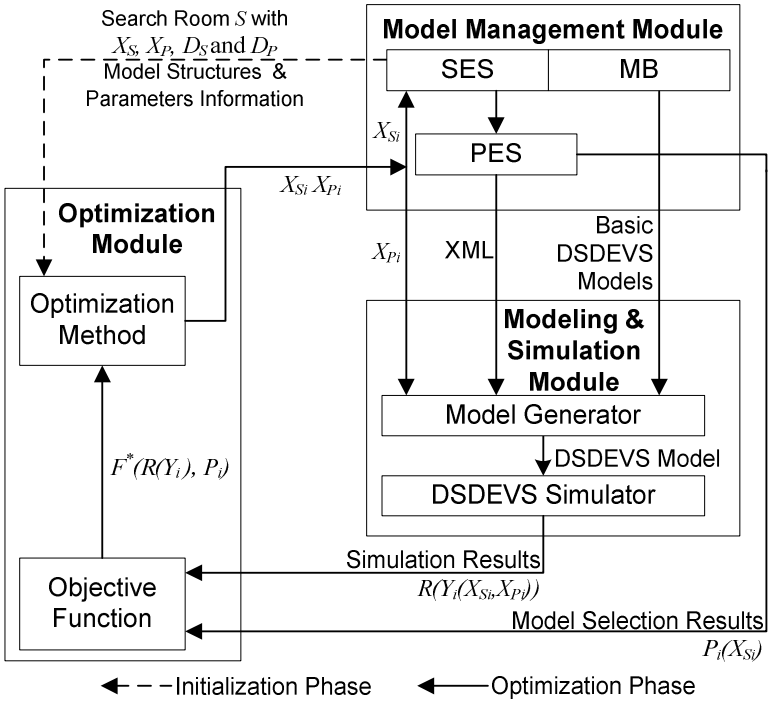

Figure 4.1 Structure of the optimization framework

The framework consists of the three fundamental components:

- Model Management Module based on the SES/MB approach introduced in Section 3
- Modeling and Simulation Module based on DSDEVS [9][16]
- Optimization Module with a Genetic Algorithm (GA) as optimization method

The appropriate interfaces to combine the above components are described next.

4.2 Interface: Optimization Module – Model Management Module

The optimization process consists of an initialization and an optimization phase. During the initialization phase, the Model Management Module has to analyze the SES tree to transform formal meta-model structure information into numerical data useable by the Optimization Module. Together with the model parameters the information is sent as initialization data to the Optimization Module. The information, coded in the four sets X_S, D_S, X_P, and D_P is used to build the set $X^* = X_P \cup X_S$ and the corresponding domain set $D^* = D_P \cup D_S$. During the optimization phase that is repeated in each optimization loop cycle, the optimization method calculates a numerical data set $X_i^* = X_{Pi} \cup X_{Si}$. The set X_i^* is sent to the Model Management Module, which determines based on this information a new model configuration, that is, a new model structure and initial model parameters.

The main task of the first transformation is to convert SES structure information to a structure parameter set X_S and the corresponding domain set D_S. This is done by a tree analysis using a breadth-first or depth-first algorithm, starting at the root node, traversing the tree and considering every node. If a node is a decision node (i.e., a specialization node, multiple aspect node or composite entity node with alternative successor nodes), a structure parameter x_{Si} is added to the structure parameter set X_S and a corresponding domain d_{Si} to the domain set D_S. The domains of specialization node and composite entity node are {1, …, number of variants}. The domain of a multiple aspect node is defined by its attached number range property.

Figure 4.2 illustrates the algorithm for creating structure parameter set X_S and the corresponding domain set D_S using a breadth-first algorithm. It starts at the root node *A*, a non-decision node. Next nodes are non-decision nodes A_{dec} and *B*. The composite entity node *C* is the

first decision node. It has two alternative successors. A first parameter x_{S1} is added to set X_S with the domain $d_{S1} = \{1, 2\}$. The next examined nodes are B_{dec}, C_{dec1}, C_{dec2}, D, E, F, G, H and I - they are non-decision nodes. The next examined node, the multiple aspect node D_{maspec} is a decision node. The value of its number range property is {2, 3, 4}. A second parameter x_{S2} is added to X_S with the domain $d_{S2} = \{2, 3, 4\}$. The next node, the specialization node E_{spec} is again a decision node. It has three alternative successor nodes. A third parameter x_{S3} is added to X_S with the domain $d_{S3} = \{1, 2, 3\}$. The last nodes analyzed, K, E_1, E_2 and E_3 are non-decision nodes. The example SES has three decision nodes. The resulting structure parameter set is $X_S = \{x_{S1}, x_{S2}, x_{S3}\}$ with the corresponding domain set $D_S = \{d_{S1}, d_{S2}, d_{S3}\}$ with the above determined domains. These sets, X_S, D_S, the model parameter set X_P and its domain set D_P are used by the optimization method as the search space definition. Additional SES tree information, that is, structure conditions and attached variables, are irrelevant during the initialization phase.

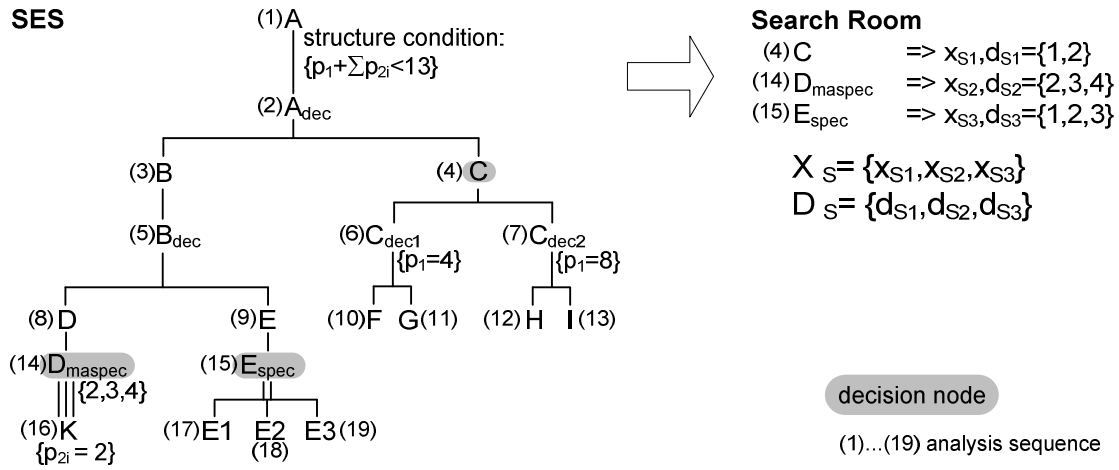

Figure 4.2 Transformation SES → set X_S and set D_S

The second transformation is the reverse of the first. The Model Management Module receives a point in the search space from the Optimization Module, that is, the numerical data set $X_i^* = X_{Pi} \cup X_{Si}$, where set X_{Si} codes the model structure and set X_{Pi} codes its parameters. It has to

synthesize the corresponding model structure and has to infer the model parameters. The transformation has to traverse the tree in the same direction as during the first in the initialization phase. At each decision node the next element of current structure parameter set X_{Si} is used to decide: (i) which successor of a composite entity node with alternative successor nodes is chosen, (ii) which successor of a specialization node is chosen, or (iii) how many successors of a multiple aspect node are incorporated into the PES. After pruning, the model structure is verified with the evaluation of the remaining structure conditions. If a structure is invalid the specific set X_i^* will be refused and this information is sent to the Optimization Module. In case of an invalid model configuration, the Optimization Module marks this point in the search space as prohibited and determines a new one.

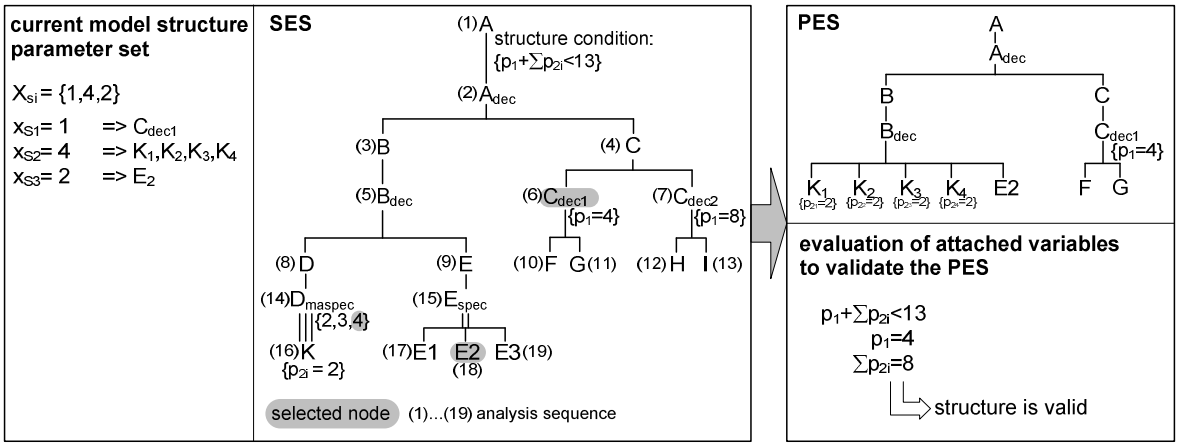

Figure 4.3 Transformation X_{Si} + SES → PES

Figure 4.3 illustrates the principle of this transformation. The breadth-first analysis starts at the root node *A* and continues as already described before. The first decision node is composition entity node *C*. The first element of X_{Si} is $x_{S1}=1$, that is, the first aspect node C_{dec1} is chosen for the PES. The next decision node is the multiple aspect node D_{maspec} and the corresponding set element is $x_{S2}=4$, that is, the PES contains four nodes *K*. The last decision node is specialization node E_{spec} and the corresponding set element is $x_{S3}=2$, that is, the PES contains the second

specialization of node E_{spec}. After pruning, the attached variables are calculated and the PES is verified by evaluating the structure condition. In the example, the aspect node C_{dec1} and four atomic entity nodes K were chosen. Therefore, the structure condition at node A is evaluated as follows: $p_1 + \sum p_{2i} = 4 + 8 < 13$ and it follows that the PES is valid.

4.3 Interface: Model Management Module – Modeling and Simulation Module

Each optimization cycle requires a change and adaptation of the simulation model. If the structure parameters in X_{Si} are changed, a new simulation model structure has to be generated. Otherwise, if just the model parameters in X_{Pi} are changed, it is adequate to re-initialize the model parameters. As illustrated in Fig. 4.1 all necessary information is sent from the Model Management Module to the Model Generator of the Modeling and Simulation Module. The Model Management Module creates XML files describing the model structure. DSDEVS basic components predefined in the MB, XML files, and current model parameters coded in set X_{Pi} are used by the Model Generator to generate the entire DSDEVS model.

The use of a standardized XML model description for information exchange decouples the two modules. It is based on W3C XML schema Finite Deterministic DEVS Models introduced in [12] and [13]. The XML interface uses the atomic and coupled model descriptions with model and port names. The coupled model description described in [13] is currently work in progress and does not contain all necessary description elements for this approach. Therefore, the composition description of coupled models used in the framework additionally defines submodel names and coupling specification. The decoupling of Model Management Module and Modeling and Simulation Module using XML files eases the modeling and verification of the basic components.

4.4 Interface: Modeling and Simulation Module – Optimization Module

The objective function, defined in the Optimization Module (see Fig. 4.1) estimates the performance of the current model configuration. The function gets its input parameters from the Modeling and Simulation Module. These are the simulation results $Y_i(X_{Si}, X_{Pi})$ and simulation response function results $R(Y_i(X_{Si}, X_{Pi}))$ respectively. Further input parameters are delivered by the Model Management Module. These are the model structure results $P_i(X_{Si})$, which are based on evaluation of attached variables after pruning the SES. An example is illustrated in Fig. 4.2. The aspect nodes C_{dec1} and C_{dec2} and the atomic entity node K define the attached variables p_1 and p_{2i}. After pruning illustrated in Fig. 4.3, the values of p_1 and p_2 are calculated as follows: $P_i(X_{Si}) = \{p_1;\sum p_{2i}\} = \{4;8\}$. These values may be used as further objective function parameters.

The result $F^*(R(Y_i), P_i)$ of the objective function is evaluated by the optimization method. As a consequence of the often stochastic nature of simulation problems, a random based optimization method is preferable. Two established random based algorithms inspired by the principle of the evolution of life are the Genetic Algorithm (GA) introduced by Holland [10] and the Evolutionary Strategy (ES) introduced by Rechenberg [19]. The origins of ES are continuous parameter problems whereas current GAs support hybrid problems. A disadvantage of the original GA is the missing memory. It is possible that in different generations the same individual is repeatedly examined. Because of the time consuming fitness estimation of an individual in simulation based optimization, the addition of a memory method is vitally important. It has to store already examined individuals with their resulting $F^*(R(Y_i), P_i)$.

4.5 Algorithmic Summary of the Framework

As described in the precedings, the proposed simulation based parameter and structure optimization framework is composed of different methods that form a uniform optimization

approach. The following algorithm summarizes the fundamental operations using a GA as optimization method.

Initialization Phase:

0. Analyze the SES and establish $X^* = X_P \cup X_S$ and $D^* = D_P \cup D_S$
1. Initialize a population of individuals (generation 0) with different $X_i^* = X_{Pi} \cup X_{Si}$

Optimization Phase (repeat until stop criterion is fulfilled):

2. Estimate the fitness of all individuals of the current generation

   Repeat for each individual

   2.1. Check memory if individual is known. In case of 'true': continue with next individual

   2.2. Prune SES with X_{Si}

   2.3. If structure condition is valid establish $P_i(X_{Si})$ or otherwise mark individual as invalid and continue with next individual

   2.4. Generate DSDEVS model

   2.5. Simulate DSDEVS model and get result $Y_i(X_{Si}, X_{Pi})$

   2.6. Evaluate the simulation response function $R(Y_i(X_{Si}, X_{Pi}))$ by repeating Step 2.5

   2.7. Evaluate the objective function $F^*(R(Y_i), P_i)$

   2.8. Store X_i^* and $F^*(R(Y_i), P_i)$ in memory
3. Select pairs with m individuals and create descendants using crossover
4. Mutate the descendants
5. Exchange individuals of the current generation with descendants based on a substitution schema to create a new generation

The next section demonstrates the application of the introduced framework with a project from

industry.

5 Application example

The example is based on developments and problems in the photofinishing industry and investigates a small part of a production process to demonstrate the approach. Photofinishing laboratories specialize in high volume production of thousands to millions of pictures per day. As a consequence of significant changes in the photography market, notably the introduction of digital cameras with a considerable reduction of analogue and an increase of digital orders during recent years, a mix of analogue and digital production facilities are used. The changes have lead to concentration from many, local working, smaller laboratories to a few, large, nationwide working laboratories and fierce competition between them. The situation is driving an urgent need to be as cost effective as possible.

Figure 5.1 shows general structure and product flow through the different departments of a typical photofinishing laboratory. The material arrives in several forms at the login department. After sorting the product mixes, some 10 to some 1000 single orders are combined into batches, each batch containing only one product type, for example, specific paper width and surface. The batch creation is done with different machine types: (i) a splicer combines undeveloped film rolls onto a film reel, (ii) a universal reorder station (URS) combines analogue reorders to a strap of film strips, (iii) a digital URS scans the analogue reorders and produce a digital batch, (iv) a digital splicer handles data carriers (CDs, flash cards etc.), and (v) software applications combine digital images received over the internet. Undeveloped analogue batches have to be developed and analogue material can be scanned. Next steps are CD production, printing, paper development, and cutting. Finally items are packed and identified for delivery to customers. There are several possible material routes through production with the same end product but

different processing time, machine and operator requirements, and costs. It is possible to employ fewer operators than available workstations and produce on time if an appropriate production structure and effective organization method are used to manage production.

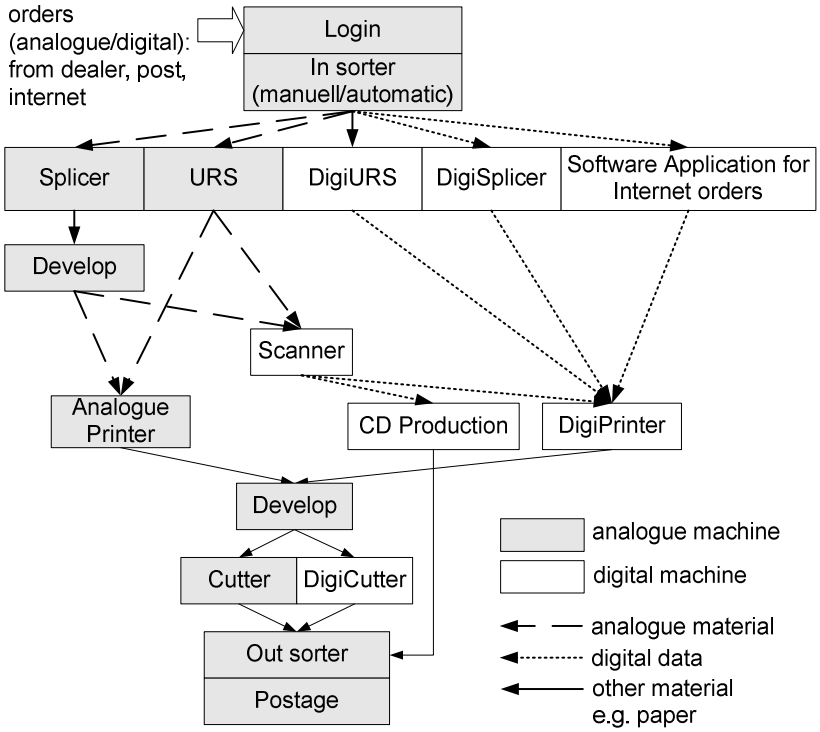

Figure 5.1 General product flows of a photofinishing lab

The example is based on developments and problems in the photofinishing industry and investigates a small part of a production process to demonstrate the approach described in this chapter. For this example the login and splicer departments are studied in detail with a structure as in Fig. 5.2. The source material, unsorted, single orders, is sorted by product type manually or automatically into boxes. The sorted orders are combined onto batch reels at splicers. An automatic sorter is handled by one or two operators, whereas manual sorting is done by the number of available operators without the need of a machine. The handling time depends on the number of machines, machine type, and the number of operators. A splicer is handled by one operator with fixed average handling time. Operators can be moved between machines. The

production time of a fixed number of orders, and, consequently, the cost, vary depending on the type and number of machines used, number of operators, and the strategy to organize operators. The task is to minimize the production time of a given number of orders whilst minimizing cost.

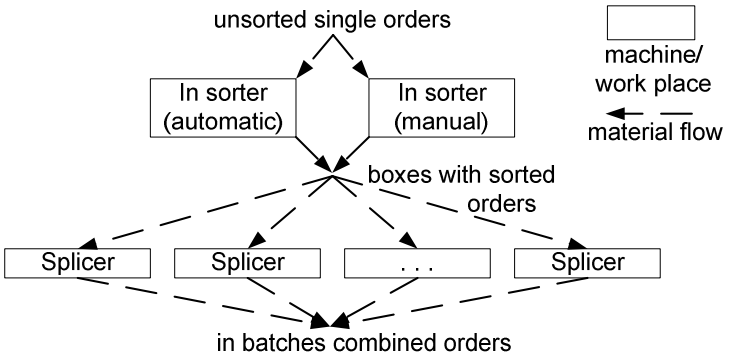

Figure 5.2 Product flow of the considered example

To validate the introduced framework the global optimum estimated through simulation of all system variants is compared with the result of an optimization experiment. In both experiments the performance rating of one variant is done by the same objective function.

The simulation output of a single run delivers the production time and cost $Y = \{y_{production\ time}, y_{costs}\}$ of the currently investigated model variant. They are passed to the objective function. This function is defined by the term:

$$F = F(Y) = \alpha_1 * y_{production\ time} + \alpha_2 * y_{costs} \rightarrow minimum$$

The factors α_1 and α_2 define the relevance of the variables. With $\alpha_1 = 1/max\_production\_time$ and $\alpha_2 = 1/max\_costs$ both variables are within the range 0..1 and have the same relevance. The maximal value of the production time can be calculated by one simulation run and the maximal value of the costs is defined by the maximal *number of operators*, a model parameter with defined range.

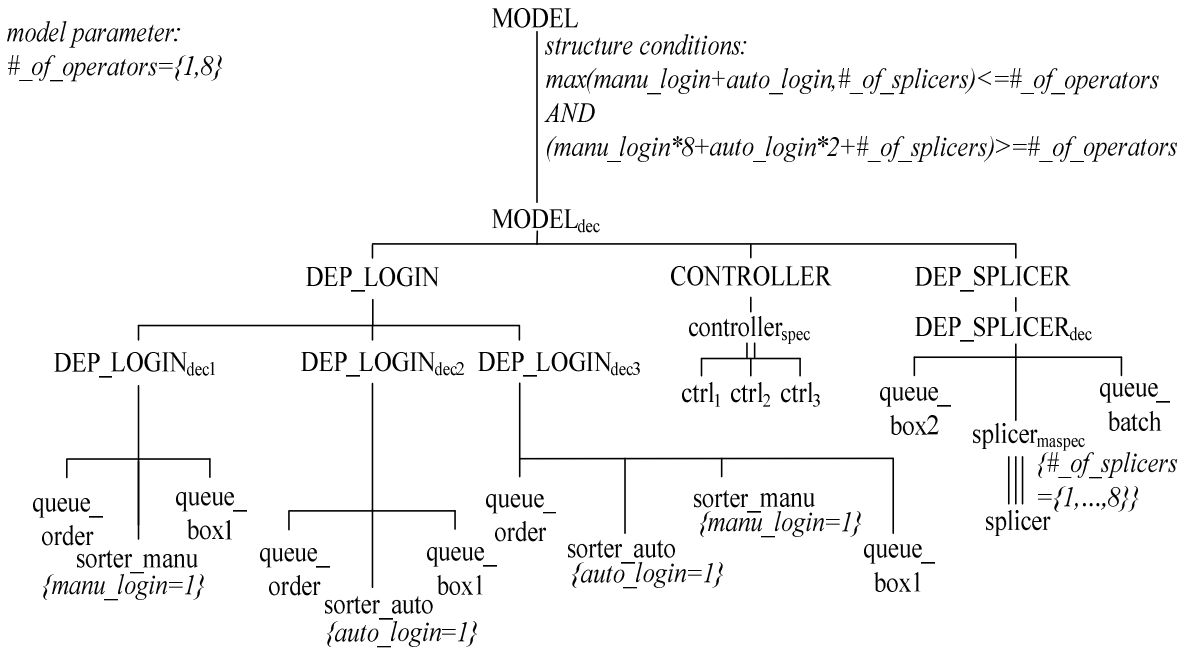

Figure 5.3 SES of the example

Figure 5.3 depicts the SES, describing possible model structures of the considered example. The model variants are characterized by: (i) the usage of automatic and/or manual sorting, (ii) the usage of one to eight splicers, and (iii) the usage of one of three different department organization strategies to move operators between departments. Depending on chosen alternatives during the pruning process several structure related attached variables will be initialized with different values. The SES defines 72 model structure variants in all. Besides, there is one variable model parameter, the *number of operators* with a range of one to eight. The combination results in 576 model variants. Not all model variants define useful combinations. For example, a model with four operators and eight splicers delivers the same result as a model with four operators and four splicers. To exclude the useless variants the root node MODEL defines a structure condition that reduces the valid number of model variants to 275.

To solve this example, the search space has to be defined in terms of a structure parameter set, a model parameter set, and their corresponding domain sets. Using the principle

introduced in Section 4.2, the structure parameter set and the corresponding domain set are defined by:

$X_S = \{x_{DEP\_LOGIN}, x_{controllerspec}, x_{splicermaspec}\}$

$D_S = \{d_{DEP\_LOGIN}, d_{controllerspec}, d_{splicermaspec}\}$ *with*

$d_{DEP\_LOGIN} = \{1; 2; 3\}$; $d_{controllerspec} = \{1; 2; 3\}$; $d_{splicermaspec} = \{1; 2; 3; 4; 5; 6; 7; 8\}$

The model parameter set and the corresponding domain set are defined by:

$X_P = \{x_{\#\_of\_operators}\}$

$D_P = \{d_{\#\_of\_operators}\}$ *with* $d_{\#\_of\_operators} = \{1; 2; 3; 4; 5; 6; 7; 8\}$

Hence, the resulting search space is defined by:

$X = X_P \cup X_S = \{ x_{DEP\_LOGIN}, x_{controllerspec}, x_{splicermaspec}, x_{\#\_of\_operators}\}$

Each model variant defines one point in the search space. With the principle introduced in Section 4 a PES can be derived and a corresponding model can be generated. One point in the search space is $X_{132} = \{2; 2; 2; 2\}$. This means that the aspect node DEP_LOGIN_{dec2} and the specialization $ctrl_2$ are chosen, the number range property value of the multiple aspect node $splicer_{maspec}$ is two, and the model parameter *#_of_operators* is also two. Figure 5.4 depicts the PES of model variant 132. The generated modular, hierarchical simulation model is illustrated in Fig. 5.5. This model variant delivers the minimal objective function value. The fitness values of all 275 model variants are depicted in Fig. 5.6.

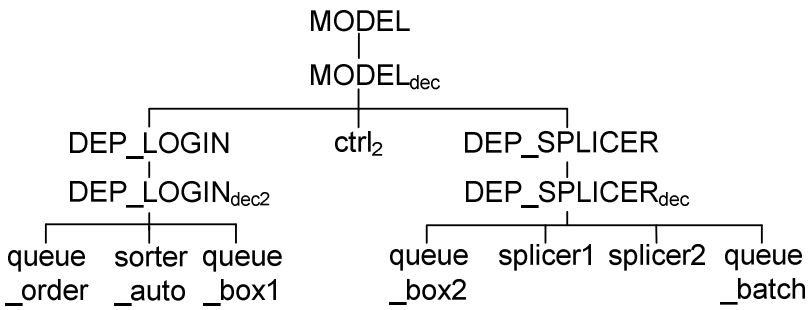

Figure 5.4 PES of 132th variant

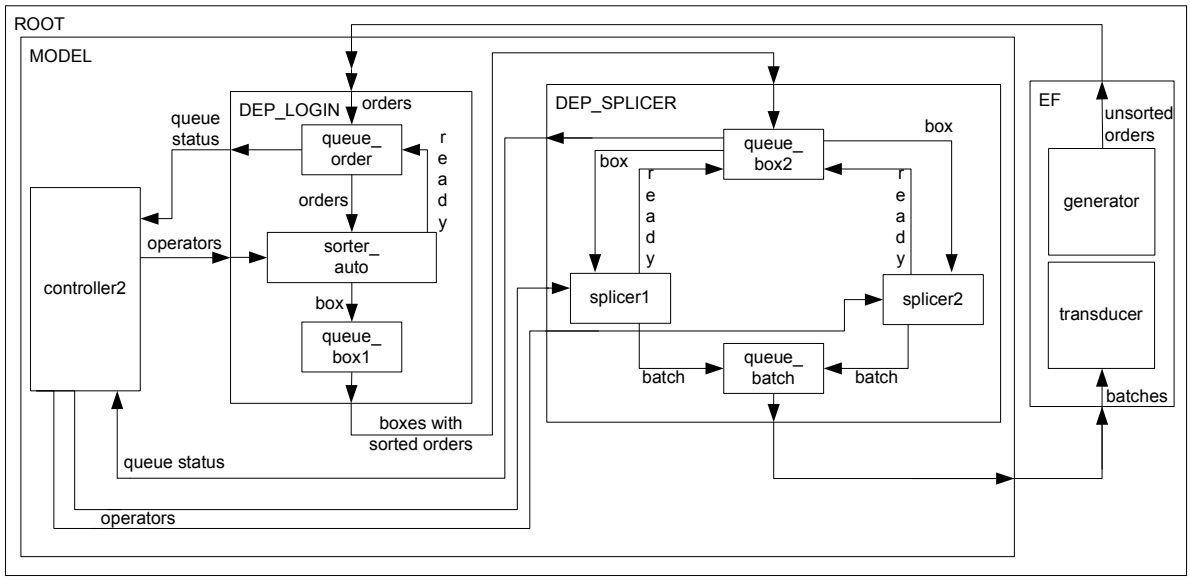

Figure 5.5 Modular, hierarchical model of 132th variant

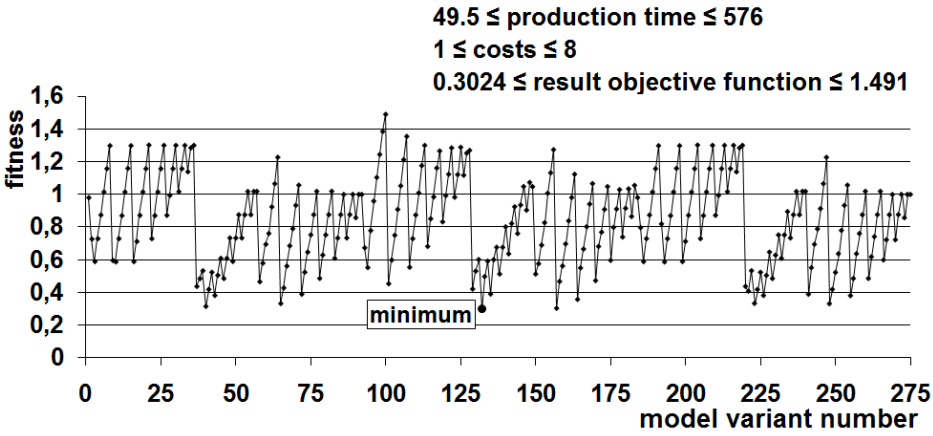

Figure 5.6 Fitness values of all variants with the optimum at X_{132}

The MATLAB® GA toolbox [24] is employed as the optimization method in this example. The default MATLAB GA parameter settings were used, except for a decreased population size of 15 and an adjusted stop criterion: if the weighted average change in the fitness function value over 20 generations is less than 0.01, the algorithm stops. The optimization experiment was repeated 100 times with different random number streams. The optimal structure and its parameter set were found after 194 simulation runs on average in contrast to 275 simulation runs of a complete

enumeration experiment. The optimal solution X_{132} with the fitness 0.3024 was found 47 times. Other sub-optimal solutions with a fitness value smaller than 0.35 were found 21 times. Non-optimal solutions were found 32 times.

The results show that the introduced optimization framework delivers an optimal solution with significantly less simulation runs in comparison to a complete simulation study of all model variants.

6 Summary

This chapter briefly summarized fundamental aspects of simulation based optimization. It introduced a novel approach for structure optimization of modular, hierarchical discrete event systems. The approach combines a model management method, modeling and simulation methods, and an optimization method to enable a concerted structure and parameter optimization. Appropriate interfaces between the different methods have been developed. Core of the interfaces are two transformations. The first one transforms formal structure information into numerical data, which are amenable to an optimization method. The second one transforms a specific numerical data set, calculated by the optimization method, into a specific model structure with its corresponding model parameters.

A prototype of the introduced framework was implemented with the Scientific and technical Computing Environment MATLAB. It consists of a MATLAB based SES toolbox for model management, a MATLAB based DSDEVS simulation toolbox, and the Genetic Algorithm and Direct Search Toolbox™ from The MathWorks™. The software prototype has been successfully used to prove the approach with first applications. The results of the described example demonstrate the advantages of the introduced approach. Using the implemented framework, the optimal structure and its corresponding model parameters are found with

significantly less simulation runs in comparison to a complete simulation study of all model variants.

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An Approach for Simulation Based Structure Optimisation of Discrete Event Systems

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Keywords: Structure Optimisation, Discrete Event Simulation, DEVS, SES, DSDEVS Matlab Toolbox

Abstract
Modelling and simulation with integrated parameter optimisation is a well established technique. This paper introduces an extended, simulation based optimisation method. Behind automatic parameter value variation the method is able to re-configure model structure during optimisation. This is achieved through a combination of optimisation, simulation and model management methods. Using this approach simulation is used to establish the performance of a current model structure and parameter value set and the optimiser searches for an optimal solution with repeated model structure and model parameter value changes assisted by the model management methods.

1. INTRODUCTION

Modelling and simulation with integrated optimisation is a well established technique in engineering applications. Such techniques are used for system design, real time planning and to control production systems. With increasingly complex, flexible production systems the requirements for modelling and simulation tools are growing. Existing applications using optimising simulation are restricted to parameter optimisations. The modeller has to change model structure manually and repeat optimisations until a solution is found. With increasing production system flexibility the number of possible structure variants increases and the potential benefit of automatic model structure optimisation would be significant.

The focus of this paper is the description of a methodology for a combined parameter and structure optimisation for modular, hierarchical discrete event systems. In contrast to current, optimising modelling and simulation environments the model structure is variable and thus it is open to optimisation. The variations of model structure and model parameter values are controlled by a superordinate optimisation module. To support the optimisation method appropriate modelling, model management/generation and simulation methods are necessary.

As a basis for model management and generation the System Entity Structure (SES) formalism, introduced by Rozenblit, Zeigler et al [6] [10] [11], is employed. The SES formalism is a generative, knowledge base framework consisting of a tree like entity structure and a model base. With its features it is able to define a set of modular, hierarchical models and to generate specific model structures. The modelling and simulation method is based on the Discrete Event System Specification (DEVS) formalism introduced by Zeigler [9] and some of its extensions [1], [4], [8] and [10]. Traditional modelling and simulation systems, and the original DEVS, only provide support for static structure models [9] [10]. That means, they offer modelling methods to build specific model structures with behavioural dynamics and aggregation methods to combine them into complex structures. But the structure information itself cannot be changed during model execution. The structural information in a modular hierarchical DEVS model remains an integral part of the system during simulation. This offers the potential of structure changes during simulation time. Dynamic Structure DEVS (DSDEVS) introduces methods to make these potential structural changes possible [1] [4] [5]. In engineering and manufacturing applications the advantage of a dynamic structure modelling and simulation method are considerable. Dynamic structure features are beneficial for several applications but the approach presented is not restricted to the usage of DSDEVS.

Section 2 provides a short preview of optimisation and optimising simulation, the approach using a combined structure and parameter optimisation method is presented and the requirements for the optimisation environment are defined. Section 3 briefly introduces the established SES formalism as a model set organisation and model generating meta-modelling method. The synthesis of the three elements, optimisation, model generation and simulation, to perform a combined structure and parameter optimisation is presented in section 4. Finally an industrial application is described in section 5.

2. OPTIMISING SIMULATION

Simulation experiments can be of different complexity. The least complex ones are ordinary simulation runs, shown in figure 2.1a. After examining simulation results the modeller manually changes the model parameter values and/or structure and starts the simulation again. These steps are repeated until a suitable solution is found. A more complex approach is simulation based parameter optimisation, described in figure 2.1b. Mathematical optimisation generally means establishing a function minima or maxima. Parameter optimising simulation means finding the optimal model input parameter value set through optimising a function of output variables estimated with a simulation method [7]. The function is named the objective function. The optimising method alters model parameter value(s) to improve the result of the objective function until a stop criteria is fulfilled. The result is a parameter optimised model. Structure changes are carried out manually by the modeller with a possible repetition of the automated parameter optimisation.

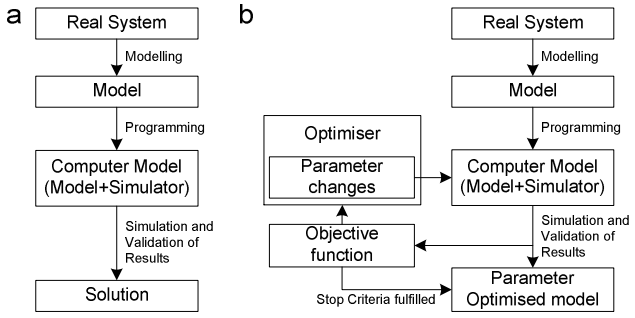

Figure 2.1 principles of (a) simulation and (b) parameter optimising simulation

The following describes a parameter optimising simulation problem O with a set of m input parameters $X = \{x_1, \ldots x_m\}$ [7]:

- parameter set X has the domain set $D = \{d_1 \ldots d_m\}$
- the search room $S = \{s = \{(x_1,v_1) \ldots (x_m,v_m)\} \mid v_i \in d_i\}$
- set Y is the stochastic, simulation output variable set defined by $Y = \{y_1 \ldots y_n\} = Y(X)$ and estimated by simulation
- an objective function F establishes a single stochastic value from output set Y : $F = F(Y) \rightarrow \Re+$
- because of the stochastic nature of Y an estimation function R, the simulation response function, typically defined by $R(X)=E(F(Y(X)))$, is optimised

Each parameter value set $X_i \in S$ can be seen as a possible solution of O. The optimiser has to search the search room S to find the parameter value set $X_{opt} \in S$ with $E(F(Y(X_{opt}))) \leq E(F(Y(X))) \ \forall X \in S$. The resulting parameter value set X_{opt} is named the global optimum of O.

This approach to optimising simulation is widely used in research and commercial applications. It is restricted to an automated parameter optimisation. Automatic structure changes during optimisation are not possible. It is a logical conclusion to extend the optimisation methods with the ability to change the model structure thus improving the result of the objective function. The result of this extension is a structure and parameter optimising simulation. The figure 2.2 as an extension of figure 2.1b describes the approach in principle.

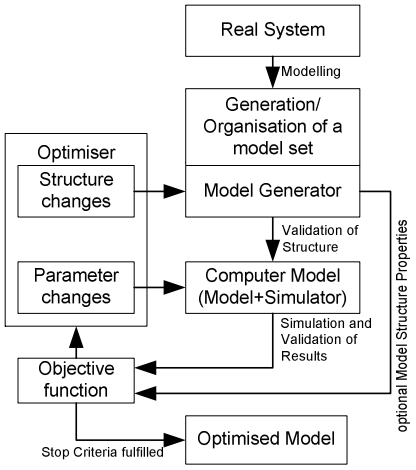

Figure 2.2 principle of a combined structure and parameter optimising simulation

In contrast to the established approach the optimising method now controls both model parameter values and the model structure. The objective function can now not only use the simulation results but also further information about the model structure. This information is based on optional attached variables, summarised during model synthesis. The optimiser loop changes both the structure and the parameter values until a stop criterion is reached. The result of this process is a combined parameter and structure optimised model.

Also, in contrast to the established approach, the modeller has to organise a set of models. One possibility is to define a model which describes a set of model variants instead of one single model of the real system. Such models that define the creation and interpretation of a set of models are named meta-models. When a model is the abstraction of an aspect of the real world a meta-model is yet another abstraction of the model itself. Through this inclusion of an automatic model generating element the optimiser can use parameter values as well as model structure changes to find an optimised solution. This idea combines established methods: (i) a modelling and simulation environment and (ii) a meta-model framework as model generation/management with (iii) an optimiser.

This approach was implemented as a prototype. The implementation uses a Genetic Algorithm (GA) as an

optimising method. A GA has a numerical stabile and robust behaviour. As a modelling and simulation environment an extended DEVS formalism is chosen. It is well suited for engineering tasks, especially the modelling and simulation of variable structure systems, and discrete event control problems [5]. As a meta-modelling framework the System Entity Structure is used. The SES formalism is a general, knowledge base framework. With its key feature to depict the three relationships (i) decomposition, (ii) taxonomy and (iii) coupling it is capable of defining a set of DEVS models [6] [10] [11].

3. SPECIFICATION OF MODEL SETS WITH SES

To represent a set of modular, hierarchical models, a method is needed to describe three relationships: decomposition, taxonomy and coupling. Decomposition means the formalism has to be able to decompose an object into sub-objects. Taxonomy means the ability to represent several, possible variants of an entity. To compose an entity from sub-entities these have to be coupled. This is the meaning of a coupling relationship. The SES formalism is able to describe these three relationships [6] [10] [11].

A SES is described by two major parts: (i) an entity structure and (ii) a model base. The entity structure (ES) is a tree like structure which contains invariable and/or variable branches. To create one structure variant the entity structure is pruned. The pruning process decides at decision nodes which or how many variable branches will be used considering the structure constraints. The result of this process is a pruned entity structure (PES) which is the basis of a composition tree. This tree contains all the information to create together with the model base contents the hierarchical model. Figure 3.1 shows the principal transformation process SES → PES → Model.

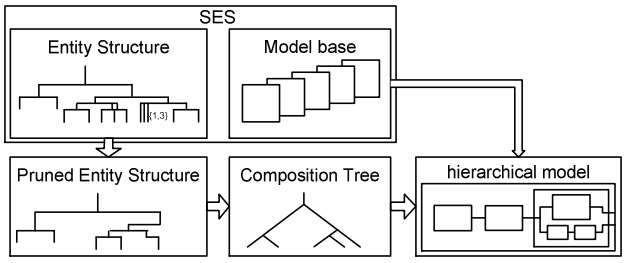

figure 3.1 pruning and model generation process

Figure 3.2 depicts the taxonomy of an ES. It is a labelled tree and consists of different entities, atomic and composite, and different edge types. The leaves of the tree are atomic entities, inner nodes are composite entities. The edge type defines further categories of the superordinate composite entity. Three different composite entity types exist:

- *specialisation entity*, shown in figure 3.2a with a double line edge. The entity A_{spec} has two specialisations A_1 and A_2. This structure is named taxonomy.
- *decomposition entity*, depicted in figure 3.2b with a single line edge. The decomposition entity B has two variants B_{dec1} and B_{dec2}, named *aspect entity*. The aspects are special kinds of decompositions like specialisations are kinds of classifications.
- *multiple aspect entity*, shown in figure 3.2c with a triple line edge. The variable number of its sub-entities is defined by an attached property.

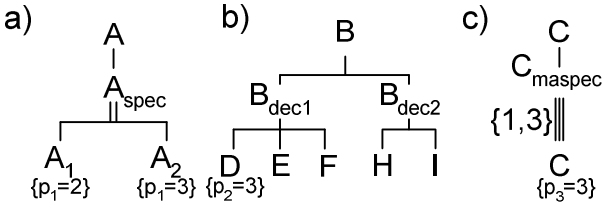

figure 3.2 entity types in a SES

An entity can have additional properties:

- *Couplings* information added to an aspect entity - they are used during the composition of the model structure
- *AttachedVariables* added to an entity, e.g. p_1, p_2, p_3 in figure 3.2 – they are used for a structure evaluation and as properties for the model
- *StructureConstraints* added to sub-entities of variable entities like specialisations and aspects – they are used during the pruning process to validate the model structure
- *DomainProperty* - multiple aspects have attached the possible number of entities.

The model base contains a set of DEVS models which corresponds to entities in leaf nodes of ES.

The following formal description of an ES is derived for further definitions in chapter 4 and provides the basis for a prototype implementation:

AtomicEntities = {$Entity_1$,… $Entity_n$ } |
Entity ∈ LeaveNodes

CompositeEntities = { $Entity_1$,… $Entity_n$ } |
CompositeEntity ∉ LeaveNodes

RootEntity ∈ CompositeEntities
The root entity represents the root of ES.

AtomicEntity=(name, {av_1,… av_n}, {sc_1,… sc_o}) | name ∈ Modelbase ∧ {av_1,… av_n} ⊆ Attached Variables ∧ {sc_1,… sc_o} ⊆ StructureConstraints
An atomic entity is defined by a name, can have attached variables and refers to a model of the Model Base.

DecompositionEntity =(name, {$AspectEntity_1$,… $AspectEntity_n$} ⊻ SpecEntity ⊻ MultiEntity) |
DecompositionEntity ∈ CompositeEntities
A decomposition entity is defined by a name and incorporates an ordered set containing one or more aspect

entities or one specialisation or one multi-aspect entity. It has to have at least one sub-entity. During the pruning process one of the aspect entities is chosen within the relevant structure constraints.

SpecEntity = (name, {Specialisation$_1$, . . . Specialisation$_m$}, {av$_1$,… av$_n$}) |
{Specialisation$_1$, . . . Specialisation$_m$} ⊆ AtomicEntities ∧
{av$_1$,… av$_n$} ⊆ Attached Variables ∧
DecompositionEntity ∈ CompositeEntities

The specialisation entity is defined by a name, incorporates an ordered set with 1-n sub-entities and can have attached variables. During the pruning process one of these sub-entities is chosen within the relevant structure constraints of its Specialisation sub-nodes.

AspectEntity = (name, {AtomicEntity$_1$,… AtomicEntity$_m$}, {DecompositionEntity$_1$,… DecompositionEntity$_n$},{av$_1$,… av$_o$}, {sc$_1$,… sc$_p$}, {Coupling$_1$,… Coupling$_q$}) |
{av$_1$,… av$_o$} ⊆ Attached Variables ∧
{sc$_1$,… sc$_p$} ⊆ StructureConstraints ∧
DecompositionEntity ∈ CompositeEntities

The aspect entity is defined by a name, incorporates ordered sets with Atomic and/or DecompositionEntities, can have attached variables and structure constraints. Coupling properties are used to compose the sub-entities and they are defined by a set of 2-tuples. Each tuple consists of sub-entity source and destination information, e.g. (SourceEntity.outputport, DestinationEntity.inputport).

MultiAspectEntity = (name, {Entity$_{min}$,… Entity$_{max}$}, {av$_1$,… av$_m$}, {sc$_1$,… sc$_n$}) |
DomainProperty={min,max} ∧
{av$_1$,… av$_m$} ⊆ Attached Variables ∧
{sc$_1$,… sc$_n$} ⊆ StructureConstraints

The multiple aspect entity is defined by a name, has one sub-entity and can have attached variables. During the pruning process the number of the sub-entities is chosen within the relevant structure constraints and possible quantities defined in domain property.

4. INTERFACE SPECIFICATIONS

The fundamental parts of this approach are the interface and method definitions I, II and III, depicted in figure 4.1. They bind the established methods together to synthesize the combined structure and parameter optimising simulation.

Before an optimisation can be carried out, information about the search room is necessary. In this approach the search room is defined by the set of model structure variants established by analysing the ES and the set of model parameters, defined by each model structure. During the optimisation process several points in the search space are examined. Each point defines one single model structure to be generated through the model generator with one parameter value set.

The formal description extension of a parameter optimising simulation problem O (section 2 and [7]) to a structure and parameter optimisation leads to O^*:

- model parameter value and domain sets $X_P=X$ and $D_P=D$ are extended by sets of model structure parameters $x_{Si} \in X_S$ and their domains $d_{Si} \in D_S$. The extended set definitions are: $X^* = X_P \cup X_S = \{x_{P1} \ldots x_{Pm}, x_{S1} \ldots x_{Sn}\}$ and $D^* = D_P \cup D_S = \{d_{P1} \ldots d_{Pm}, d_{S1} \ldots d_{Sn}\}$ with m model parameters in set X_P and n model structure parameters in set X_S. The sets X_P and D_P are defined by the current model. To provide sets X_S and D_S the ES tree has to be analysed.
- The objective function F^* is defined by $F(Y(X_P),P(X_S))$ with simulation results $Y_P=Y(X_P)$ and optional attached variables $P_S=P(X_S)$ established from pruning the ES.
- The search room $S = S_P \cup S_S$ is spanned by sets of model parameter and model structure variants.

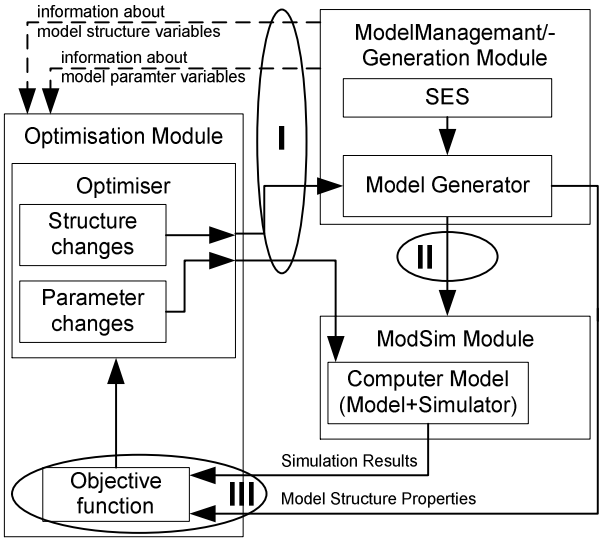

figure 4.1 interfaces between the three methods

The interface (**I**) between Optimisation Module and Model Management/Generation Module (figure 4.1 I) is a two-way interface defining both, (i) the generation of information about model structure parameter and domain sets from an ES and (ii) the method to prune a SES based on information about a specific point of the search room. One task of the interface is the generation of the two sets X_S and D_S based on information from an ES tree. This is done by analysing the tree starting at *RootEntity*, traversing it in a defined direction and sub-entity order and considering every entity property. When it is a decision node, i.e. of type *SpecEntity*, *DecompositionEntity* or *MultiAspectEntity*, a parameter x_{Si} is added to the structure parameter set X_S and a domain d_{Si} to the domain set D_S. The domains of *SpecEntity* and *DecompositionEntity* nodes are {1 . . . number of variants}.

The domains of *MultiEntity* nodes are defined by their attached *NumberRangeProperty*.

There are two general principles that can be applied to traverse the tree: (i) depth-first and (ii) width-first analysis. An advantage of the width-first analysis is the arrangement of the variables. When it can be assumed that variant decisions at a higher level of the ES have larger effects on model performance than decision near the leaves, then the width-first analysis sorts the variables accordingly: variables on the left hand side of the ordered set correspond to higher levels of the ES, variables on the right hand side correspond to decision nodes nearer the leaves. Figure 4.2 describes the idea of creating model structure parameter set X_S and the corresponding domain set D_S based on ES tree information.

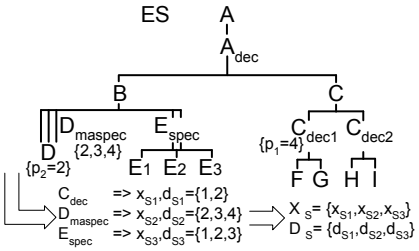

figure 4.2 transformation ES to sets of X_S and D_S

Using a width-first analysis of the ES depicted in figure 4.2 the algorithm starts at non-decision node A_{dec}. Next nodes are non-decision node B and decision node C. The decomposition node C has two *AspectEntity* nodes C_{dec1} and C_{dec2}. A first parameter x_{S1} is added to set X_S with the domain $d_{S1} = \{1, 2\}$. Next examined node D_{maspec} is a decision node. This *MultiAspectEntity* node has the number range property {2, 4}. A second parameter x_{S2} is added to X_S with the domain $d_{S2} = \{2, 3, 4\}$. The next node examined is *SpecEntity* node E_{spec} with three specialisations E_1, E_2 and E_3. A third parameter x_{S3} is added to X_S with the domain $d_{S3} = \{1, 2, 3\}$. The last nodes C_{dec1}, C_{dec2}, E_1, E_2, E_3, F, G, H and I are non-decision nodes. Hence the example ES has three decision nodes and the resulting model structure parameter set is $X_S=\{x_{S1},x_{S2},x_{S3}\}$ with domain set $D_S=\{d_{S1},d_{S2},d_{S3}\}$. On the basis of these sets together with the model parameter and domain sets the optimiser can search the search space.

During the optimising process several points in the search room are examined. Each point is defined by a specific set $X_i=X_{Pi} \cup X_{Si}$. The set X_{Si} codes a specific model structure and set X_{Pi} represents its model parameter values. In each structure optimisation step a specific set X_{Si} is passed from the optimisation module to the model management/generation module to generate an appropriate model structure with model parameters X_{Pi}. The transformation of set X_{Si} to ES information is the reverse of the previously described process. The same direction to traverse the tree and same sub-node handling order are essential. At each decision node the next element of current structure parameter value set X_{Si} is used to decide which specialisation or aspect branch is chosen or how many multi-aspect branches are used for the composition tree. The model generation from the resulting PES is performed as the established SES model generation process described in chapter 3. Figure 4.3 illustrates the idea.

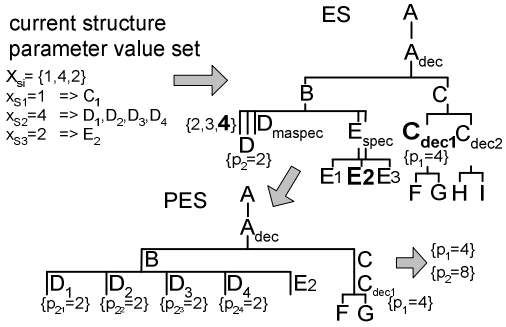

figure 4.3 transformation of the point X_{Si} to PES

Using the same width-first analysis, as was used during the creation of the sets X_S and D_S, the ES is pruned with the current structure parameter value set X_{Si}. The first decision node in the ES of figure 4.3 is *DecompositionEntity* C. The first set element is x_{S1}=1 i.e. the variant 1 of C is used in the PES. The next decision node is *MultiAspectEntity* D_{maspec} and the corresponding set element is x_{S2}=4 i.e. the PES contains four times node D. The last decision node is *SpecEntity* E_{spec} and the corresponding set element is x_{S3}=2 i.e. the PES contains the second specialisation of node E.

The generated model and the parameter values are sent to the modelling and simulation model over the interface **II**. This interface between Model Management/Generation Module and Modelling and Simulation Module (figure 4.1) decouples the modules using standardised XML files. It is based on W3C XML schema Finite Deterministic DEVS Models [2] [3]. The interface uses the atomic and coupled model interface descriptions with model and port names and additionally, for coupled models, the composition description with sub-model names and couplings. The coupled model description described in [3] is currently work in progress and does not contain all necessary description elements for this approach. The coupling definitions are extended by separated external input, external output and internal couplings. With the pruned ES a set of XML files is generated. Figures 4.4 and 4.5 show atomic and coupled model examples. With information in the XML files an executable model structure for the simulator is generated from the model base.

```
<?xml version="1.0" encoding="utf-8"?>
<atomic modelName="server" xmlns="AtomicDevs">
   <inports/>
   <outports>
      <outport>job_out</outport>
   </outports>
</atomic>
```

figure 4.4 XML atomic model example

```
<?xml version="1.0" encoding="utf-8"?>
<Digraph name="MODEL" xmlns="CoupledDevs">
   <Models>
      <Model><devs>server</devs></Model>
      <Model><devs>transducer</devs></Model>
   </Models>
   <inports/>
   <outports/>
   <EIC/>
   <IC>
      <Coupling>
         <SrcModel>server</SrcModel>
         <outport>job_out</outport>
         <DestModel>transducer</DestModel>
         <inport>job_in</inport>
      </Coupling>
   </IC>
   <EOC/>
</Digraph>
```

figure 4.5 XML coupled model example

The decoupling of model management/generation and modelling and simulation modules using XML files eases implementation and validation and enables the use of different simulator implementations.

The objective function (**III**) (figure 4.1) estimates the performance of the current model structure and model parameter values set. The function has two input sources: (i) simulation results and (ii) information calculated during model generation based on additional variables. They are optionally attached to ES tree nodes and calculated during the pruning process. In the example in figure 4.3 entities C_1, C_2 and D has two attached variables p_1 and p_2, both are used as additional objective function parameters. During pruning the values of p_1 and p_2 are calculated: $P_{Si}=P(X_{Si})=\{4;8\}$.

5. APPLICATION EXAMPLE

This example is based on developments and problems in the photofinishing industry and investigates a small part of a production process to demonstrate the approach. Photofinishing laboratories specialise in high volume production of thousands to millions of pictures per day. As a consequence of significant changes in the photography market, notably the introduction of digital cameras with a considerable reduction of analogue and an increase of digital orders during recent years, a mix of analogue and digital production facilities are used. The situation is driving an urgent need to be as cost effective as possible. Figure 5.1 shows product flow through the different departments of a typical laboratory. The material arrives in several ways at the login department. After sorting the product mixes, some 10 to some 1000 single orders are combined into batches, each containing only one product type (e.g. specific paper width and surface). It is done with different machine types: (i) a splicer combines undeveloped film rolls, (ii) an universal reorder station (URS) combines analogue reorders to a roll of film strips, (iii) a digital URS scans the analogue reorders and produce a digital batch, (iv) a digital splicer handles data carriers (CDs, flash cards etc.) and (v) software applications combine digital images received over the internet. Undeveloped analogue batches have to be developed and analogue material can be scanned. Next steps are CD production, printing, paper development and cutting. Finally items are packed and identified for delivery to customers.

There are several possible routes for the material through production with same end product but different times, requirements and costs. It is possible to employ fewer operators than working places are available and produce on time with them when an appropriate production structure and effective organisation methods are used.

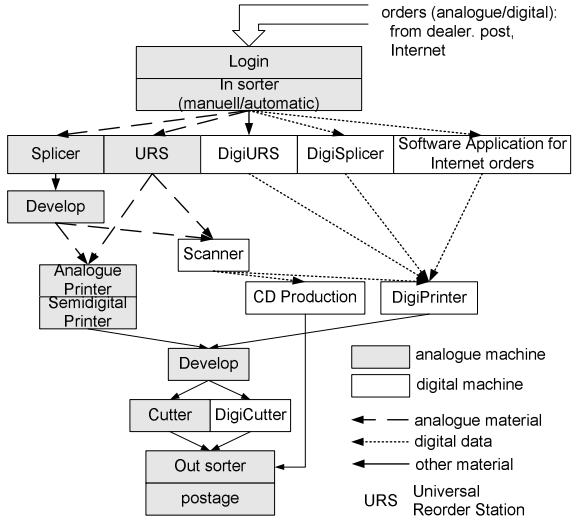

figure 5.1 product flows in a photofinishing lab

This example is restricted to the login and splicer departments with a structure as depicted in figure 5.2:

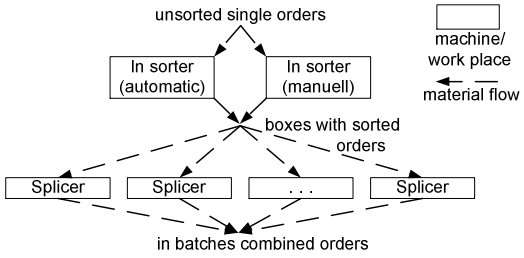

figure 5.2 product flow of the example

The source material, unsorted, single orders, is sorted by product type manually or automatically into boxes. These sorted orders are combined to batch rolls at splicers. An automatic sorter is handled by one or two operators, whereas manual sorting is done by the number of available operators without the need of a machine. The handling time depends on the number of machines, machine type and the number of operators. A splicer is handled by one operator with fixed average handling time. Operators can be moved between machines.

The production time of a fixed number of orders (and consequently the cost) varies depending on the type and number of machines used, number of operators and the strategy to organise operators. The task is to minimise the production time of a given number of orders whilst minimising the costs.

To validate the methodology the global optima estimated through simulation of all system variants is compared with the result of the optimisation approach. In both experiments the performance rating of one variant is done by the same objective function.

The simulation output of a single run delivers the production time and costs $Y = \{y_{production\ time}, y_{costs}\}$ of the currently investigated model variant. They are passed to the objective function. This function can be coded as follows:

$$F = F(Y) = \alpha_1 * y_{production\ time} + \alpha_2 * y_{costs} \rightarrow \Re+$$

The factors α_1 and α_2 are factors to define the relevance of the input variables. With $\alpha_1 = 1/max\_production\_time$ and $\alpha_2 = 1/max\_costs$ both variables are within the range 0..1 and have the same relevance. The maximal value of the production time can be calculated by simulation and the maximal value of the costs is defined by the maximal *number of operators*, a model parameter with defined range.

Figure 5.3 depicts the ES, describing all possible model structures of this example. Variants with automatic and/or manual sorting, one to eight splicers and three different control strategies to move operators (moving after finished login, no movement and moving depending on size of queue box2) are allowed.

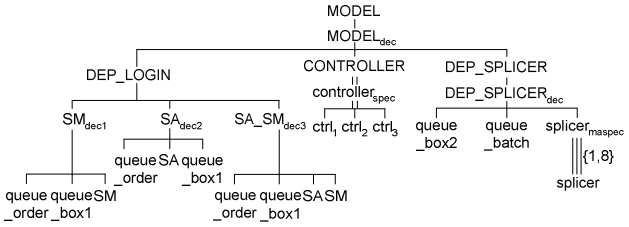

figure 5.3 ES of the example

The ES defines 72 model structure variants. The model has one parameter *number of operators* with a range of one to eight. The combination results in 576 model variants. The fitness of all simulated variants and minimal fitness value are depicted in figure 5.4. The optimal model structure X_{266}

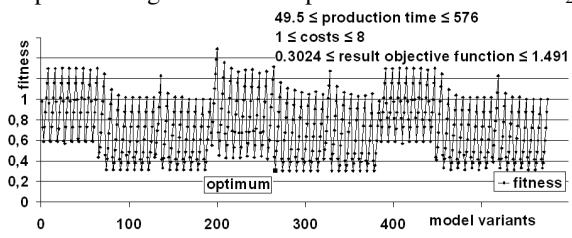

figure 5.4 fitness of all variants with optimum at X_{266}

is shown in figure 5.5. The optimal value of the model parameter *number of operators* is two.

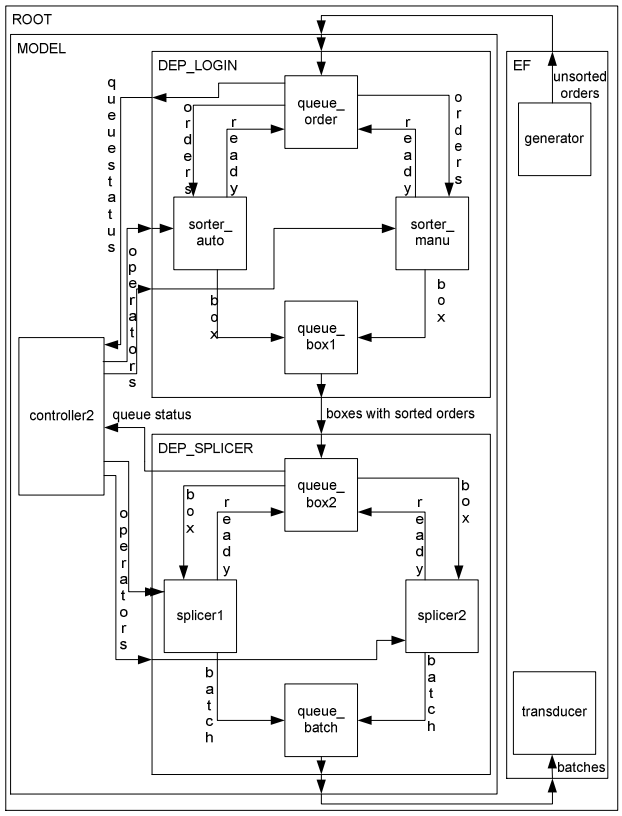

figure 5.5 model structure of 266th variant

To solve this example, the search room with model structure parameter and model parameter sets and their domains has to be defined. Using the principle introduced in section 4 the model structure parameters and domain sets are defined by:

$X_S = \{x_{DEP\_LOGIN}, x_{controller_{spec}}, x_{splicer_{maspec}}\}$
$D_S = \{d_{DEP\_LOGIN}, d_{controller_{spec}}, d_{splicer_{maspec}}\}$ with
$d_{DEP\_LOGIN} = \{1; 2; 3\}$
$d_{controller_{spec}} = \{1; 2; 3\}$
$d_{splicer_{maspec}} = \{1; 2; 3; 4; 5; 6; 7; 8\}$

The model parameter and domain sets are defined by:

$X_P = \{x_{operators}\}$
$D_P = \{d_{operators}\}$ with $d_{operators} = \{1; 2; 3; 4; 5; 6; 7; 8\}$
Hence the resulting search room is defined by:

$X = X_P \cup X_S$
$X = \{ x_{DEP\_LOGIN}, x_{controller_{spec}}, x_{splicer_{maspec}}, x_{operators}\}$

Each point of the search room defines one model structure and parameter variant. With the principle introduced in section 4 a PES can be composed and the model can be created. One point is $X_{266} = \{2; 2; 2; 2\}$. This means that the second decomposition of *DEP_LOGIN* and the second specialisation of $controller_{spec}$ are chosen, the sub-entity number of the multiple aspect $splicer_{maspec}$ is two and the model parameter *number of operators* is also two. The

associated PES is depicted in figure 5.6. and the corresponding model structure in figure 5.5.

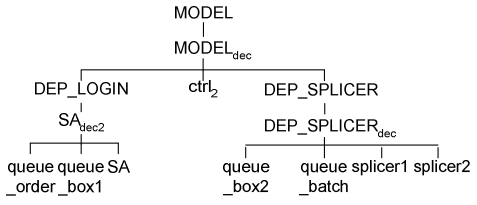

figure 5.6 PES of 266th variant

For optimisation the genetic algorithm of the Matlab GA toolbox was used with default settings (except the population size of 15). The optimisation experiment was repeated 100 times with different random number generation initialisations of the GA toolbox. The optimisation process finds the global optimum but needs less simulation runs than the complete enumeration. The global optimum X_{266} with the fitness 0.3024 was found 42 times. Other local optima with a fitness value smaller then 0.31 were found 50 times. Non-optimal solutions were found eight times. The optimal structure and parameter set was found for the first time after 51 simulations on average and after 172 simulations the result didn't change. An example of the development of fitness values during one optimisation run is shown in figure 5.6.

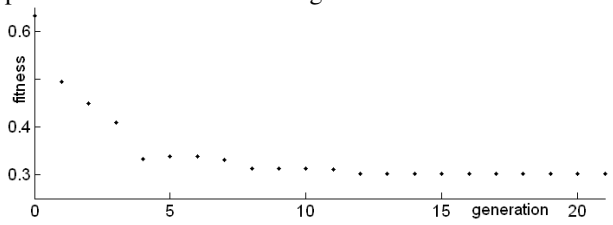

figure 5.6 mean generation fitness values of one GA run

The results show that the approach can find an optimal model variant using less simulation runs than a complete simulation of all model variants.

6. CONCLUSION

This paper has introduced a structure optimisation method for discrete event simulation systems. The approach combines three established methods and extends optimisation to the fundamental model structure to enable combined structure and parameter optimisation.

It has been shown that using a meta-model as a superordinate method to define simulation models, parameter optimisation can be extended to a combined structure and parameter optimisation. Three main elements have been determined: (i) a model generating meta-modelling technique based on SES formalism, (ii) a DSDEVS based modeller and simulator, (iii) an optimisation method. The interfaces between them have been defined: (i) A two-way interface between optimiser and meta-modeller provides information about the search room for the optimiser and supports model structure and parameter value set generation for a specific point of the search room. (ii) An interface between meta-modeller and simulator decouples both and permits the use of different, modular hierarchical modelling and simulation methods.

A prototype of the approach was implemented with the Scientific and technical Computing Environment Matlab. The implementation with the MatlabDSDEVS toolbox [4] [5], MatlabSES, implemented within the scope of this research, and Matlab Genetic Algorithm and Direct Search Toolbox has been successfully used to prove the approach with first examples. Implementation of more complex examples and examination of other optimisation methods will be carried out in the scope of further research.

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An approach for modelling and simulation of variable structure manufacturing systems

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Abstract. Discrete Event Simulation (DES) is an established method for manufacturing system analysis. The development of complex DES models requires a modular modelling and simulation approach. Modularity supports clear model structures, provides high model reusability and enables independent development and testing of components. A comprehensive theory of modular hierarchical modelling and accompanying simulator algorithms was introduced by Zeigler with the Discrete Event Specified System (DEVS) formalism. A disadvantage of the classical DEVS theory is the lack of capability to formulate complex structure variability. This paper provides a brief summary of the classical DEVS theory and introduces extensions to give comprehensive support to modelling and simulation of complex structural changes in modular hierarchical systems. The paper concludes by discussing the advantages of the variable structure modelling approach using an application in the photo-finishing industry.

Keywords: variable structure systems, discrete event simulation, DEVS, DSDEVS.

1 INTRODUCTION

Many real systems change their structure during lifetime. These can be technical systems [1] such as manufacturing, computing or communication systems, digital controllers [2] or natural systems such as in biology and ecology [3]. In a manufacturing environment structure changes can occur at different levels. At the management level shop floors can be opened or closed, at the shop floor level different production sections can be used to produce the same product and at the production level different operation sequences can be performed to produce a specific product or machines and operators can be replaced or moved to another production cell.

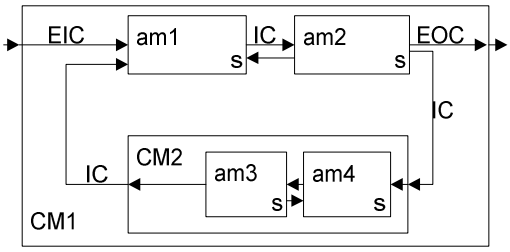
Traditional modelling and simulation systems provide only support for static structure models [4] [5]. That means, they offer modelling methods to specify modules or components with a behavioural dynamic and aggregation methods to compose them to complex structures. But the composition structure itself cannot be changed during model execution. Of course with these systems it is also possible to emulate structural system dynamics. But the specification has to be transformed to the behavioural modelling level. Sometimes it is hard to describe complex structural dynamic such as the various production possibilities in manufacturing systems on the behavioural modelling level. Furthermore, this procedure often leads to complex model components and reduces the component generality that results in reduced component reusability.

The goal of this paper is to introduce a structure dynamic modelling approach based on Zeigler's Discrete Event Specified System (DEVS) formalism. Chapter 2 briefly summarizes general aspects of the classical DEVS theory and its accompanying simulation approach. In chapter 3 the extension of the classic DEVS concept to a Dynamic Structure DEVS (DSDEVS) approach is introduced and the advanced modelling possibilities are discussed. After that the dynamic structure modelling approach is demonstrated using a complex photo-finishing laboratory application in chapter 4.

2 DISCRETE EVENT SIMULATION

General View. Discrete event systems are characterized by a continuous time base and discrete state changes [4]. In Discrete Event Simulation (DES) practice there are four dominant modelling techniques, called modelling worldviews [5]. These are process-interaction method, event scheduling method, activity scanning and the three phase method. A specific, material oriented view of the process-interaction method is often called transaction oriented. Each of the modelling worldviews has specific advantages and disadvantages and makes certain forms of model description more naturally expressible than others. In manufacturing simulation the process-interaction method is widely used. In modern simulation tools it is often combined with component-oriented approaches. The DEVS theory is able to handle all four above mentioned worldviews [4]. One of the most general and powerful features of the DEVS formalism is the modular, hierarchical model construction.

DEVS. Every DEVS system is described by two different types of entities, atomic and coupled models. Each model type has a clearly defined input and output interface and the internal structure is completely encapsulated. An atomic model describes the behaviour of a non-decomposable entity via event driven state transition functions. A coupled model describes the structure of a more complex model through the aggregation of several entities and their couplings. These entities can be atomic models as well as coupled models. All this together allows the modular and hierarchical construction of complex systems.



am	atomic models
CM	coupled models
EIC, EOC, IC	external input/output and internal couplings
S	systems states

Fig. 1 Example DEVS model

Figure 1 shows a simple DEVS model, a production cell with integrated queues, a server with quality checker and a rework server. The complete cell is depicted by the coupled model *CM1*. The model has an external interface with one input and one output port to receive and send work pieces. It contains two atomic models and one coupled model, the queue *am1*, the server *am2* and the rework facility *CM2*. The coupled model *CM2* consists of two further atomic models the queue *am3* and the rework server *am4*. When *CM1* receives a message (a work piece) at its input port it is forwarded over the external input coupling to queue *am1*. When *CM2* generates an output message at its output port, a reworked work piece is forwarded to the second input port of *am1* over an internal coupling.

The DEVS theory in [4] defines a simulator concept for the computation of modular-hierarchical DEVS models. Figure 2 shows the computational model structure of the model example from figure 1 according to the DEVS simulator concept. Each atomic model is connected to a *simulator* entity. This entity handles messages like 'initialisation', 'compute next state' or 'get time of next event'. Each coupled model is connected to a *coordinator* entity. It has the same interface as a *simulator*. But the *coordinator* entity handles messages, not itself, but forwards them to its subordinated *coordinators* or *simulators*. On top of the hierarchy the *root coordinator* initiates, controls and ends a simulation cycle. With this concept the modular hierarchical structure of the model remains a part of the computational model during simulation runtime in contrast to a transformation of the modular model to a monolithic computer implemented model.

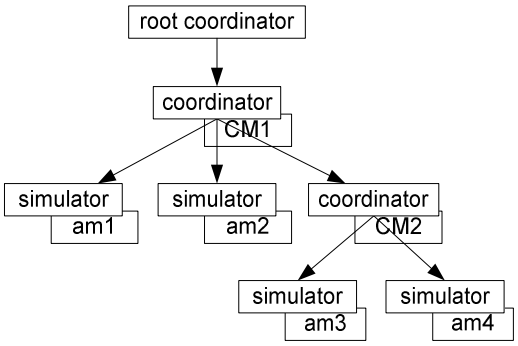


Fig. 2 Hierarchical simulator structure of the example DEVS model in fig.1

Formal Concept of DEVS Theory. The description of an atomic model is a 7- tuple [4]:

$$AM = (X, Y, S, \delta_{ext}, \delta_{int}, \lambda, ta) \quad (1)$$

X, Y and S specify the sets of discrete inputs, outputs and states. The δ_{ext} function handles external input events. It can induce an internal state change by generating an internal state event. An internal state event can induce an output event and is handled by the state transition function δ_{int}. Output events are generated using the output function λ. After external and internal events the internal events are rescheduled with the time advance function ta.

The description of a coupled model is a 9-tuple [4]:

$$CM = (d_n, X_N, Y_N, D, \{M_d \mid d \in D\}, EIC, EOC, IC, select) \quad (2)$$

d_n represents the name of the coupled model, X_N and Y_N are the sets of inputs and outputs, D specifies the name set of subsystems, M_d represents a subsystem, EIC, EOC and IC are the external input, external output and internal couplings and finally the $select$ function prioritize concurrent internal events of the subsystems.

The classic DEVS approach only supports the specification of a behavioural system dynamic in atomic systems and the specification of a component aggregation in coupled systems. It is not possible to describe a structural system dynamic, such as the deletion or creation of components or couplings, at the coupled system level, although all necessary structural information is available during runtime. The only possibility to realise a structure dynamic is to specify it with logical constructs at the atomic model level. This abolishes the advantages of reusability and model clarity and increases modelling complexity.

3 DYNAMIC STRUCTURE DEVS

Several approaches extend the classic DEVS to Dynamic Structure DEVS (DSDEVS). Barros [2] [6] and Pawletta [1] [7] use an extension of the coupled system definition while the atomic model definition remains unchanged. Uhrmacher [3] and others introduce an agent based approach. They define extensions for both atomic and coupled systems. But in general all extensions allow nearly the same possibilities to specify structural dynamics at coupled system level such as creation, destroying, cloning and replacement of subsystems, movement to other coupled systems, and changes in the couplings and interface definition of subsystems.

This research is based on the approach of Pawletta, where a coupled model is defined by the following 6-tuple:

$$CM_{dyn} = (\{d_n\}, S_N, \delta_{x\&s}, \delta_{int}, \lambda, ta) \quad (3)$$

with

$$S_N = X_N \times Y_N \times H_N \times D \times \{M_d \mid d \in D\} \times EIC \times EOC \times IC \times select \quad (4)$$

The current structure of a coupled model is interpreted as a structure state $s \in S_N$. The additional introduced set H_N defines specific structure related state variables. Structure changes can be induced by external, internal or external events of subordinated components. In analogy to the dynamic of atomic systems internal structure events are scheduled by a time advance function ta and their proposed structure changes are specified with a structure state transition function δ_{int}. Output events caused by internal events are generated using the output function λ. Structure state changes induced by external events or output events of subcomponents are handled by the transition function $\delta_{x\&s}$. However it is unreasonable to make changes in the subsystem set or coupling relations by this

function directly. This could lead to ambiguous event handling because external events could influence simultaneously the dynamic of subcomponents and the structure state. That's why the $\delta_{x\&s}$ function is only allowed to modify structure related state variables in the set H_N to trigger an internal structure state event at the same time. Simultaneous internal events of sub-models and of the coupled model itself are controlled by the *select* function.

The structure variable modelling approach and its accompanying simulation algorithms were developed as a Matlab toolbox using Matlab's object oriented programming features. The theoretical *simulator* and *coordinator* definitions are directly mapped to software classes. User specified models have to be derived from these predefined classes. Matlab as a common scientific and technical programming environment offers a large amount of computation methods and toolboxes, e.g. for optimisation and parallel computing. With the implementation of the DSDEVS approach as a Matlab toolbox it is possible to use these toolboxes within the DSDEVS simulator [7] [8].

4 APPLICATION EXAMPLE

Photo-finishing laboratories specialise in high volume production of some thousands to millions of pictures per day. As a consequence of the significant changes in the photography market during recent years they use a mixture of analogue and digital production facilities. Because of the growing complexity of these systems it is no longer possible to organise production manually in an optimal way as was usual some years ago. To analyse the system, optimise throughput and costs it is necessary to simulate the production process.

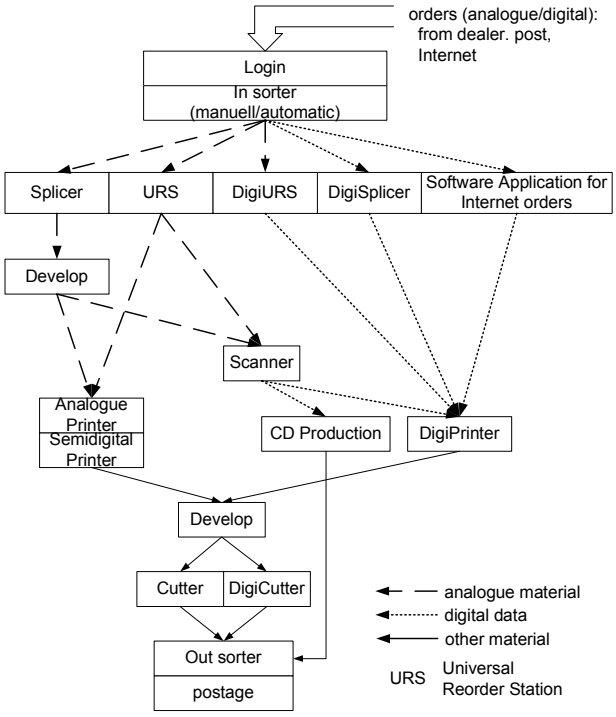


Fig. 3 Overview of the product flow and the departments of a photo-finishing laboratory

Figure 3 shows the product flow through the different departments of a laboratory. It depicts only an overview of the high volume product flow. The material arrives over several channels at the login department. After logging in and sorting the product mixtures, the single orders are combined to batches, depending on the order type (e.g. analogue or digital), the film type (e.g. 135 or APS) and the end product (e.g. paper width). It is done with different machine types: *(i)* a splicer combines undeveloped film rolls, *(ii)* a universal reorder station (URS) combines analogue reorders to a roll of film strips, *(iii)* a digital URS scans the analogue reorders and produce a digital batch, *(iv)* a digital splicer handles data carriers (CDs, flash cards etc.) and *(v)* software applications combine digital images received over the internet. Undeveloped analogue batches have to be developed and analogue material can be scanned. Next steps are printing, paper development and cutting. Finally all items are packed into a customer envelope.

Figure 4 shows the overview of a variable structure model for a photo-finishing process. It specifies *(i)* alternative ways to handle incoming material, *(ii)* some ways can be used in a different sequence but with the same result, *(iii)* the number of operators is less then necessary to handle all machines at the same time and so they have to move between departments and *(iv)* machines can be removed from or put back into production.

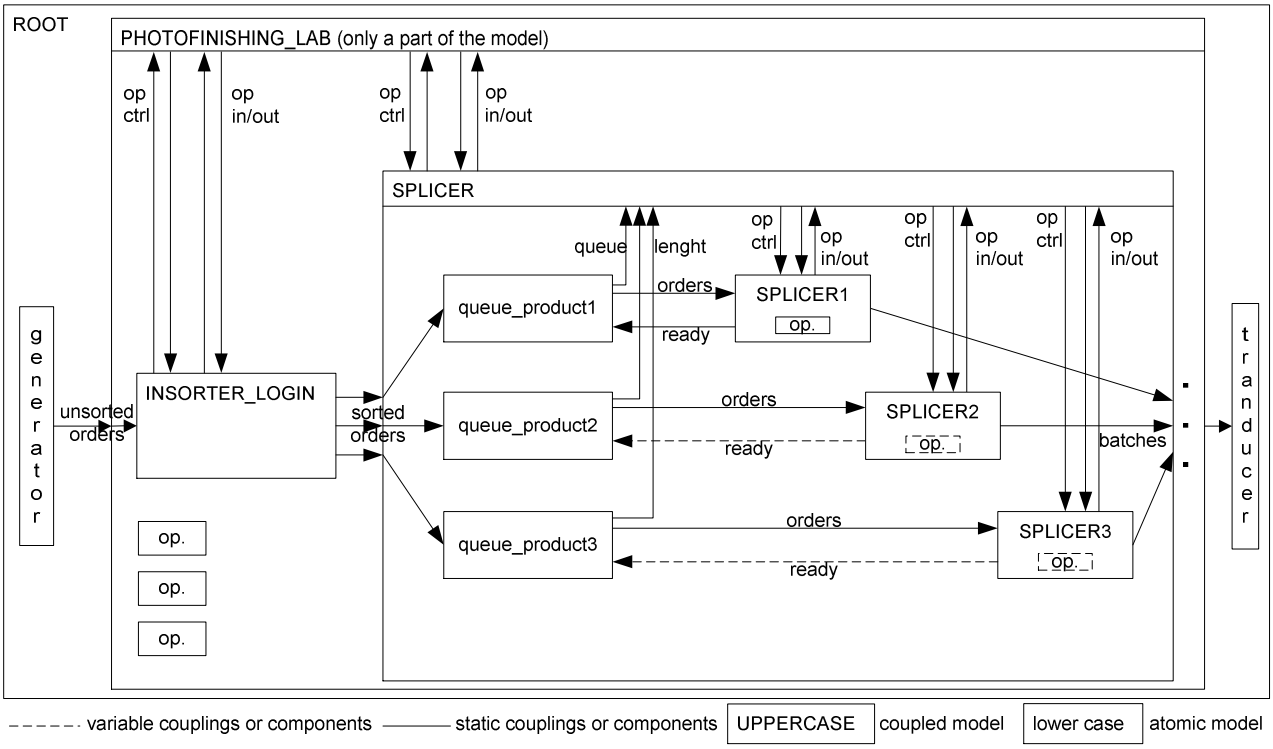


Fig. 4 Part of a photofinishing lab DSDEVS model

Because of the complexity of the complete system figure 4 shows only a fragment of the complete DSDEVS model, mainly the splicer department. The atomic model *generator* generates unsorted orders of different types as input events of the production process model *PHOTFINISHING_LAB*. The coupled model *INSORTER_LOGIN* implements the manual and automatic order login and sorting operations. The coupled model *SPLICER* depicts the splicer department. It needs a minimum limit of sorted orders in its input queues to work smoothly. The outputs of this model go to next sub-models which are not represented in figure 4. An operator is depicted by an atomic model *op*. The operator handling, requesting them from or sending to other departments, is implemented at a general level for the complete laboratory in the *PHOTFINISHING_LAB* model and at a lower level in the department sub-models such as *INSORTER_LOGIN* and *SPLICER*. Control messages for operator handling are sent over the *op ctrl* couplings and the operator sub-models *op* themselves over the *op in/out* couplings. At production start there is not enough material available in the splicer queues. Consequently operators have to be moved to the *INSORTER_LOGIN* model to increase the sorting throughput. *SPLICER2* and *SPLICER3* models are deactivated and the appropriate connections are deleted. When the length of *queue_product2* and/or *queue_product3* is long enough the coupled model *SPLICER* requests one or two *op* models from the parent model *PHOTOFINISHING_LAB*, adds them to the *SPLICER X* sub-model, activates the *SPLICER X* sub-model and creates the necessary couplings. When the length of the *queue_productX* model falls below a defined limit the *op* model will be released to the parent model, the *SPLICER X* sub-model will be deactivated and the internal coupling to the *queue_productX* sub-model will be disconnected.

In contrast to traditional modeling concepts the DSDEVS approach maps the real system structure one to one in the model. Not only the behavioural system dynamics of machines and products are directly depicted in the model but also the structural system dynamics of the production management and the movement of shared resources are comprehensible. The entire model structure and individual components reflect system reality in a more natural manner. Thereby independent component development, testing and reuse are improved.

5 CONCLUSIONS

The DEVS formalism with the extensions to DSDEVS by Pawletta was briefly introduced and the advantages of the variable structure, hierarchical modelling approach were shown using a manufacturing application. The real system structure with its structural and behavioural system dynamics maps one to one onto the model. Modules can be developed and tested independently of other parts in the complete system which eases the model development process and supports extensive model reuse. They can form a model library to ease the creation of further manufacturing systems. The modelling approach and its necessary simulation algorithms are implemented as a Matlab toolbox. Due to homogeneous integration in Matlab it can be combined with all other Matlab computation methods. The next step in this research programme is the development of optimisation methods in combination with the structure variable modelling and simulation approach to investigate structure optimisations of complex modular, hierarchical systems.

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DEVS-Based Modeling and Simulation in Scientific and Technical Computing Environments

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ABSTRACT

This paper describes our current research in the area of Discrete Event System Simulation (DEVS) and its implementation for programmable Scientific and technical Computing Environments (SCEs) with a focus on variable-structure and hybrid systems.

Engineers, unlike scientists, are usually familiar with the use of SCEs such as Matlab rather than high level programming language simulation libraries. DEVS-based modeling and simulation until now has not been available for SCEs. This research has led to the development of a fully compatible toolbox for the Matlab environment with the potential to interact with other toolboxes. The paper reviews the advantages of DEVS/SCEs integration and concludes by describing the potential benefits in applications with other toolboxes.

1 INTRODUCTION

Modeling and simulation is widely applied in engineering science and, in. the majority of cases, the problems to be solved are complex. In contrast to other modeling methodologies such as statecharts or petri nets DEVS formalisms have not been widely accepted by the engineering community. This despite the fact that the DEVS theory offers well-founded formalisms for a wide variety of engineering problems. An overview of the formalisms that underpin DEVS theory is given by Zeigler et.al. in [1].

For engineering tasks, particularly the modeling and simulation of hybrid system dynamics [2], of variable-structure systems [3,4] and discrete event control problems [5] are of greater interest.

We assume that the reason for the relatively marginal acceptance of DEVS theory in engineering is a result of the type of software tools available. Wainer's [6] summary of current DEVS tools developments shows that these tools are based on high level programming language libraries for pure simulation tasks.

In engineering science the use of SCEs has been growing rapidly for the last 15 years, while the utilization of high level programming languages is decreasing. Currently the best-known SCEs are Matlab/Simulink*, Scilab/Scicos** and Octave+.

SCEs provide a large number of predefined algorithms for numerical, graphical, statistical, symbolical and other computations for us in a single uniform environment interactively. In addition, the features of an SCE are easily extendable by integrating user-defined algorithms coded using a powerful integrated programming language.

In terms of modeling and simulation, SCEs provide efficient methods for continuous system simulation. These methods can easily be combined with other computation methods, e.g. optimisations, fuzzy methods, etc.. For discrete event system simulation, support is limited. However for Matlab, the most popular SCE, there is a combined discrete event / continuous simulation toolbox prototype available (MatlabGPSS, 1996-1999 [7]). This toolbox is based on the process-oriented modeling paradigm. Matlab's graphical simulation environment Simulink also provides Stateflow (Stateflow*, 1997) – a toolbox with limited discrete event features based on statecharts. In the latest release (R14-SP3, fall 2005), another discrete event toolbox – SimEvents* – is provided.

Since 1994 this research has focussed on the integration of DEVS formalisms within SCEs. As a first prototype, a function-oriented DEVS toolbox for Matlab4 was implemented. The key motivation was to employ the tool to introduce practical DEVS theory knowledge to engineering graduates. After Mathworks introduced an object-oriented extension for Matlab5's programming language in 1995 the work led to the implementation of an object-oriented DEVS toolbox for pure discrete event and static-structure DEVS networks. Subsequently we advanced the toolbox step by

* Matlab/Simulink, Stateflow, SimEvents are trademarks of the Mathworks Inc.
** Scilab/Scicos is a trademark of INRIA, France.
+ Octave is free software under GPL developed by J. W. Eaton and many others

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step to structure dynamic networks and then to hybrid system dynamics using several practical projects.

In addition to the educational application, toolbox prototypes have been utilized for fundamental research. The objective of the research is the implementation of an environment for modeling and simulation based on DEVS for variable-structure and combined discrete event/ continuous systems. Another aspect of the research is the implementation of process control using real-time synchronized DEVS models. In terms of the simulation of variable-structure hybrid systems we are working on the realization of a DEVS simulator using the advanced ordinary differential equation solvers from Matlab's ODE toolbox. Modeling formalisms and simulator algorithms for this domain are already published in [4,8]. The research on simulation model based process control is documented in [9,10].

Section two reviews the characteristics of SCEs, and section three describes the development of the MatlabDSDEVS-hybrid toolbox for modeling and simulating hybrid and variable-structure systems. Section four illustrates the potential to benefit from use with other Matlab toolboxes. The underlying modeling ideas and simulation algorithms are explained and the integration with optimisation algorithms and methods for parallel computing are discussed.

2 CHARACTERISTICS OF SCEs

SCEs include a large number of computing algorithms and can be easily improved by user-defined extensions implemented with the SCE specific programming language. These languages are largely array oriented and in some cases achieved using object-oriented features. They support dynamic data type binding and the syntax is very similar to mathematical notation. In contrast to classical programming languages (e.g. FORTRAN, C, C++), their primary aim is not to produce memory and runtime optimized code, but to support efficient tests and implementations of complex problems. In conjunction with the ability to execute user-defined routines immediately and interactively, a SCE constitutes an excellent basis for rapid prototyping.

Some SCEs such as Matlab provide additional features to produce more suitable code. One of these features is the compilation of SCE routines into faster intermediate code or into an executable stand-alone program. Another approach is the dynamic binding of external compiled code. This technique can also be used to couple SCEs with other applications. Figure 1 shows the general architecture of an SCE.

The core of an SCE is the parser, interpreter and routine module. Fundamental and runtime critical system routines are integrated as built-in functions (object code). Other system and user supplied routines are implemented as SCE- or intermediate code. The interpreter and the output together with the input module establish the user interface. Instructions can be processed in interactive mode by typing at the command line or in batch mode, if the parser and interpreter get their input from a file. Calculation results are printed, visualized on screen or written to file by the output module. The memory management provides a permanent global workspace and function related temporary local workspaces. A detailed description can be found in [11].

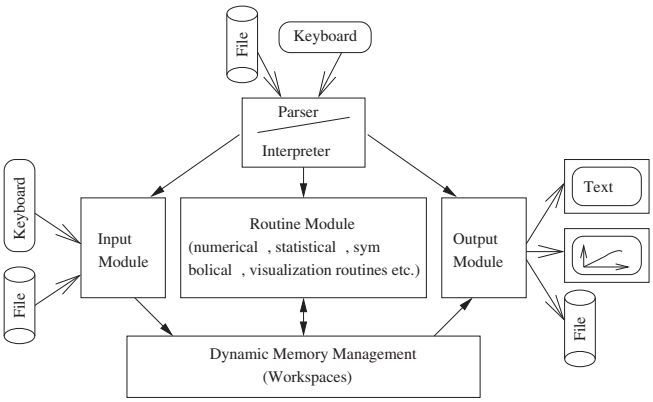

Figure 1. Architecture of an SCE

3 MatlabDSDEVS-HYBRID TOOLBOX

3.1 Underlying Formal Concept

Our modeling approach for modular hierarchical hybrid systems with structural variability at the coupled system level is based on the work in [2,3,4] and classical DEVS-theory [1].

Prähofer [2] defined a *hybrid atomic system* by the tuple

$$A_{hybrid} = (X, Y, S, f, c_{se}, \lambda_c, \delta_{x\&s}, \delta_{int}, \lambda_d, ta)$$

where X, Y and S specify the set of inputs, outputs and states which may be continuous or discrete. Continuous dynamics are mapped by the rate of change function f and the output function λ_c. Discrete events are internal, external and state events. State event conditions are defined using the state event condition function c_{se}. External events and state events induce state transitions using the function $\delta_{x\&s}$. Internal events activate the discrete output function λ_d and also the state transition function δ_{int}. After each discrete state transition internal events are re-scheduled by the time advance function ta. Local structural changes of the continuous dynamics can be modelled by structuring the dynamic description using logic variables inside the rate of change function f , the state event condition function c_{se} and the continuous output function λ_c.

Coupled structure static systems describe a static aggregation of atomic and/or coupled systems, and they permit the construction of hierarchical structures. If couplings are restricted to equivalence relations, a coupled

system consists of a set of subsystems and couplings. A coupled system is defined [2] by the tuple

$$N = (X_N, Y_N, D, \{M_d \mid d \in D\}, EIC, EOC, IC, select)$$

where X_N and Y_N designate the set of input and output quantities. D represents the name set of the dynamic subsystems, and M_d represents a dynamic subsystem. *EIC*, *EOC* and *IC* are the sets of continuous and event oriented coupling relations, subdivided into external input, external output and internal couplings. Finally, *select* is a special function to prioritize a subsystem in case of simultaneous internal events in different subsystems.

To allow structure variability, some extensions of a coupled system's definition have been introduced. In the context of this work, structural changes at the coupled system level contain the creation, cloning, deletion and replacement of atomic or coupled subsystems, their movement between coupled systems and the dynamic changes of couplings between system components. Obviously, the subsystem set and the coupling relations should be interpreted as *structure state*. Hence, a *structure variable coupled system* can have different structure states $s_0, s_1, \ldots, s_n \in S_N$.

In order to store special structure dynamics information, e.g. the number of structure changes achieved, it is appropriate to introduce an additional set of structural state variables H_N. In addition the *select* function can depend on the structure state. Consequently, the set of sequential structure states S_N of a structure variable coupled system has the form:

$$S_N = H_N \times D \times \{M_d \mid d \in D\} \times EOC \times EIC \times IC \times select$$

Structure changes in coupled systems can be induced by external, internal or state events. State events that affect structure can be caused by output events of subsystems or threshold events of: *(i)* continuous outputs of subsystems, *(ii)* continuous inputs of the coupled system or *(iii)* structure related states of the set H_N.* They can be considered an analogy to event-oriented dynamics of atomic systems.

Events influenced by the internal structure of a coupled system are planned by a time advance function *ta*, and their proposed structure changes are specified with a structure state transition function δ_{int}. For the generation of structure related output events caused by internal events, a discrete output function λ_d is introduced. For example, it is possible to send subsystems to other coupled systems. In order to avoid ambiguity in the coupled system as a result of instantaneous internal subsystem events and structure related internal events, the coupled system must occasionally be included in the selection function *select* to sequence internal events.

Structure state changes induced by external or state events are handled by a coupled system's transition function $\delta_{x\&s}$., however it is unreasonable to make changes in the subsystem set or their coupling relations by the $\delta_{x\&s}$ function directly. This could lead to ambiguous event handling because external events could influence subcomponents and the structure state simultaneously. To avoid the definition of a further *select* function it is appropriate to convert changes in the subsystem sets and coupling relations with only the internal state transition function δ_{int}. A coupled system's $\delta_{x\&s}$ function should only modify structure related variables in the set H_N, which trigger internal structure state events at the same time. Simultaneous internal events are controlled by the *select* function introduced above.

On the basis of the definition for coupled systems without structure variability, and the extensions introduced above, we find the following formal definition for coupled variable structure systems

$$N_{dyn} = (X_N, Y_N, \{d_N\}, S_N, \delta_{x\&s}, \delta_{int}, \lambda_d, ta)$$

where d_N stands for the name of the coupled system. A detailed description of the modeling approach and its application on a real engineering system can be found in [4].

3.2 Modeling and Simulation Concept

Computation algorithms for modular, hierachical DEVS models involving variable structure and hybrid system extensions were established in [1-3]. The key idea is to map a model specification to interacting program objects to reflect the system's components and their coupling relations. This approach is satisfactory for all complex structure changes during simulation runtime. However problems arise for the effective calculation of continuous model parts if they are distributed in different program objects and if non-causal integration methods are used. Non-causal algorithms are implicit integration methods and predictor/corrector integration methods [1]. In addition numeric library algorithms are not yet directly usable because they, like Matlab's ODE solver toolbox, require model preparation using specific data structures. To solve this problems this research has lead to the introduction of new data structures and methods.

Class Definitions

Figure 2 shows the MatlabDSDEVS-hybrid toolbox class definitions and function libraries. It follows that complete class definitions contain some more variables and methods such as event chain management, statistical calculations or debugging. In addition some variable and method identifiers are renamed in figure 2 in order to be self-explanatory. Because many identifiers are known from

* Structure changes depending on threshold events of continuous outputs of subsystems or continuous inputs of the coupled system are not supported by the toolbox currently.

general DEVS theory in [1] this paper will only discuss essential extensions and modifications.

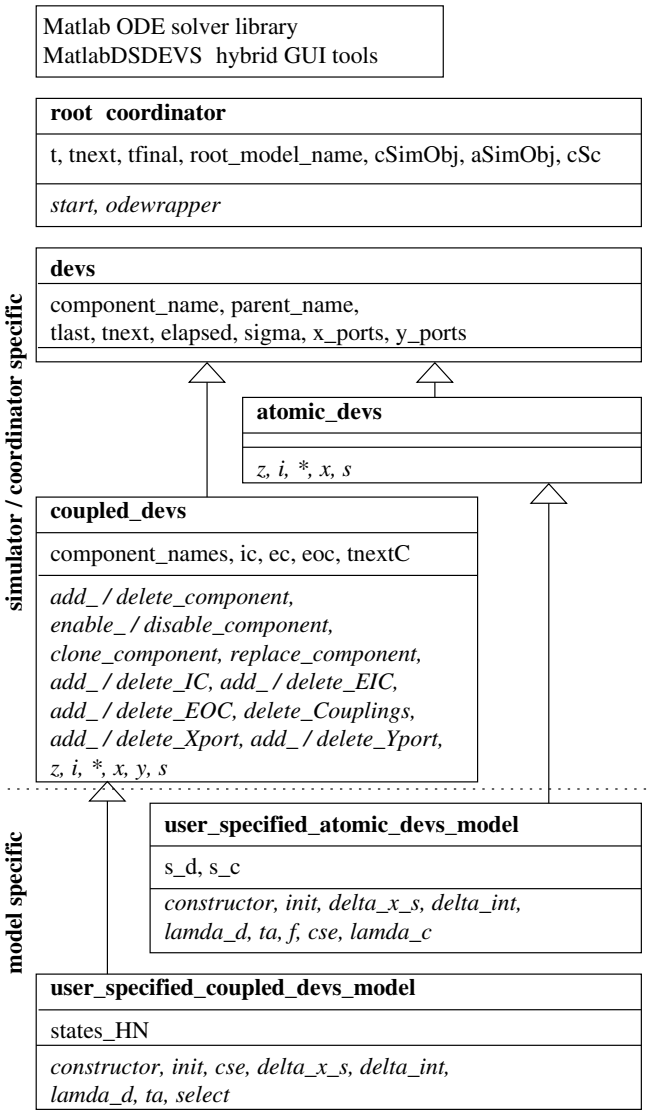

Figure 2. Major Class Definitions and Function Libraries

Class methods can be sub-divided into different groups: *(i)* Methods for creation and rearrangement of model structure in class `coupled_devs`, *(ii)* Message-based simulation methods `z, i, *, y, x, s` in class `atomic_devs` and `coupled_devs` and *(iii)* User-defined modeling methods corresponding to the formal DSDEVS-hybrid specification in section 3.1. Most methods in *(i)* are self-explanatory. Only the `replace_component` method is highlighted as it supports the replacement of systems that belong to a system family - see [4].

In the toolbox the same base classes are used for modeling and simulation. The `devs` class acts as a base class. Classes for modeling have to inherit from the two classes `atomic_devs` and `coupled_devs`. Using this strategy, each instance of a user-defined class inherits its computation methods and attributes, i.e. the inherited parts correspond to the associated simulators or coordinators in accordance with the general theory in [1]. Because each instance of a user-defined class contains both a specific model part and an inherited computation engine, we term it a simulation object.

Some Modeling Aspects

In the Matlab-environment object-oriented programming is a difficult task as a result of Matlab's rules for defining classes. A separate M-file for each class method has to be created, consequently class definitions may become quite complicated and difficult to follow. Accordingly some simple GUI tools have been implemented to support the modeling process. These GUI tools offer a model editor that automatically creates the file structure with appropriate function templates for atomic and coupled models. That means, for example in a hybrid atomic model, the following files are created: *model_name.m* (constructor), *init.m, f.m, cse.m, lamda_c.m, delta_x_s.m, delta_int.m, lamda_d.m* and *ta.m*. These files will be edited by the modeler to specify the desired model behaviour. The following code shows the model specification of a hybrid atomic system describing a bouncing ball with one continuous and one discrete output port.

```
% model equations
% height:   q1(t0)=0;   dq1/dt = q2;
% velocity: q2(t0)=20;  dq2/dt = -9.81;
% when event q1 == 0 then q2 = -0.95*q2

constructor in file bball.m
function obj = bball(in)
%obj stores reference of this object
obj.sigma = inf; %discrete states
  %incarnate object
obj = class(obj,'bball',atomic_devs(in));
  %continuous states
obj = set_c_state(obj,[0;20]);%[height; vel.]
obj = set_mealy(obj,0);%isn't Mealy type
set(obj,'c_yports',1);%no. of cont. y ports
set(obj,'d_yports',1);%no. of disc. y ports

initialization fcn. in file init.m is empty

rate of change function in file f.m
function dq = f(obj,t,q,x)
  %t current time, x input vector
  %q local continuous state vector
dq = [q(2);-9.81] % der. of [height;velocity]

state events condition function in file cse.m
function ret = cse(obj,t,q,x)
  %continuous state value height
  %    | zero-crossing direction from + to -
  %    |     | integration termination event
  %    |     |  |
ret = {q(1),-1 ,1};
```

continuous output function in file lamda_c.m

```
function outp = lamda_c(obj,t,q,x)
outp(1) = q(1); %current height cont. y port
```

external and state event state transition function in file delta_x_s.m

```
function obj = delta_ext(obj,x,event_idx)
  % no external events
switch event_idx  %handle state event actions
case 1
  q   = get_c_state(obj);
  obj = set_c_state(obj,[0; -0.95*q(2)]);
end
obj.sigma = 0; %activate internal event
```

intern. state trans. fcn. in file delta_int.m

```
function obj = delta_int(obj)
obj.sigma = inf;
```

discrete output function in file lamda_d.m

```
function obj = lamda_d(obj)
obj = set_d_output(obj,1,'down');
```

time advance function in file ta.m

```
function t = ta(obj)
t = obj.sigma;
```

Discrete event–oriented model parts are specified in a similar way to other DEVS modeling and simulation systems. Models with continuous parts have to be characterized as of Moore or Mealy type in the constructor. The continuous system dynamic is described by a vectorial differential equation in the rate of change function. State event conditions are defined in the *cse* function using three parameters. The first parameter is the zero-crossing variable, the second determines the zero-crossing direction and the third specifies if integration has to terminate or not. State event actions are handled in the *delta_x_s* function. Different state events are distinguished by evaluating the input parameter *event_idx*. In this case we have only one state event that sets the state variable *height (q1)* to *0* and determines the new value of the state variable *velocity (q2)*. Additionally, in this case, an internal state event is triggered.

Interface to Matlab ODE Solver Toolbox

Matlab provides a powerful set of ODE solver methods to control continuous integration, detection and the localization of state events. To take advantage of this methods, the continuous model descriptions (functions: *f.m, cse.m, lamda_c.m*) and continuous state vectors of all components need to be available in a closed form. That means all continuous model functions have to be encapsulated in just one wrapper function and references to all continuous state variables have to be concentrated in just one global continuous state vector. Data structures and methods necessary to perform this task are provided by the `root_coordinator`. The closed model form is represented by the `odewrapper` method using the three vectors `cSc`, `aSimObj`, `cSimObj`. The vector `cSc` stores references to all continuous state variables, while references to atomic and coupled simulation objects are stored in the vectors `aSimObj` and `cSimObj`. Collecting this information takes place during the model generation and initialisation phase and after each structure change in the simulation phase.

Model Generation and Initialisation Phase

Major aspects of message passing during the model generation and simulation phases are represented in figure 3.

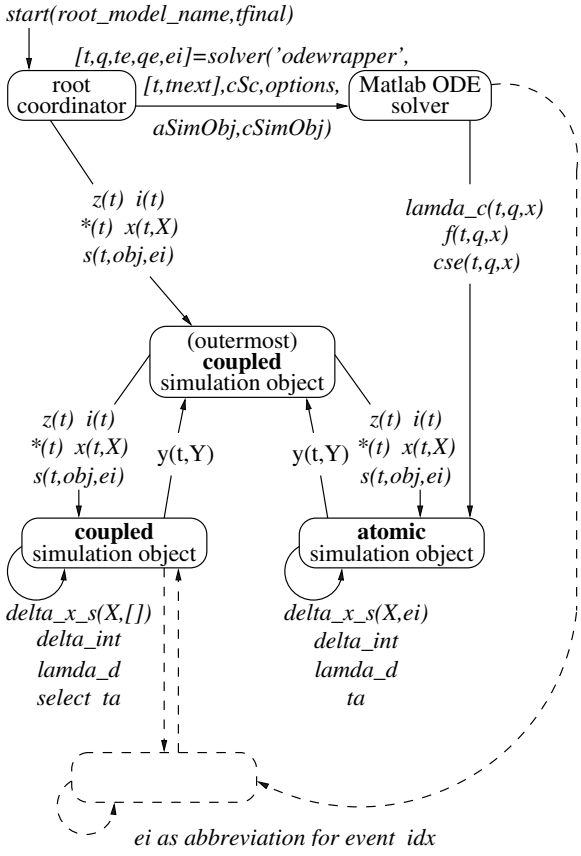

Figure 3. Message Passing During Model Execution

Model generation and initialisation is controlled by the `start` method of the `root_coordinator` object. Initially the `root_coordinator` configures the modular, hierarchical computing model structure. It calls the constructor of the outermost coupled simulation object, creates its subcomponents and their couplings and starts a recursive constructor call for all other subcomponents. Subsequently all objects are initialized by a recursive `i` message. Each object's `i` method calls the component specific `ta` and `init` methods to determine the object's next internal event time and to initialise its state and statistical variables. In contrast to classical DEVS approaches, the coupled simulation objects may contain structure related state variables in `states_HN`. They also store two next internal event times: *(i)* `tnext` for the next internal event of

a subcomponent and *(ii)* `tnextC` for the next internal structure event. The next event time sent to the super-ordinated simulation object is the minimum of these two values.

In the next step the `start` method initiates the configuration of the special data structures `cSimObj`, `aSimObj` and `cSc`. This is achieved by traversing the modular computing model multiple times using a recursive `z` message. As a consequence, the vector `cSc` stores references to all continuous state variables of atomic simulation objects. Also the vectors `aSimObj` and `cSimObj` store references to the atomic and coupled simulation objects engaged in defining or evaluating continuous variables.

A second outcome is the creation of direct references between the continuous input and output variables where input variables obtain references to the output variables. After completion the algebraic relations are sorted. To achieve this the references in the vector `aSimObj` are initially arranged with respect to atomic simulation objects of types Moore-Automata (λ_c: $S_c \rightarrow Y_c$) and Mealy-Automata (λ_c: $X_c \times S_c \rightarrow Y_c$). In a second sorting step the references to objects of type Mealy-Automata are arranged with respect to their dependent relations. In the same way the three vectors `cSimObj`, `aSimObj` and `cSc` are reconfigured during the simulation phase if structural changes in the modular computing model have occurred. In essence it is possible to generate multiple replicas of the three vectors. This is of advantage, if there are no interrelations between some continuous state variables and if they need to be calculated using different integration methods or numerical step widths.

Simulation Phase

After model generation and initialisation the `start` method enters the simulation loop. If the current simulation time `t` is smaller than the next event time `tnext` a continuous simulation phase proceeds until the next event time. A solver method from the Matlab ODE toolbox is called and the `odewrapper` method is passed as a callback function. In addition the reference vectors `cSc, aSimObj`, `cSimObj` and a solver specific `option` structure are passed.

```
[t,q,te,qe,ei] = solver('odewrapper',...
    [t,tnext],cSc,options,aSimObj,cSimObj)
```

In each integration step the solver calls the `odewrapper` method which in turn sends a `lamda_c` and a `f` message to all registered atomic simulation objects to calculate their continuous outputs and derivatives. After each integration step it also sends a `cse` message to all registered atomic simulation objects to check their continuous state event conditions. The values returned by the solver after an integration phase delivers the continuous trajectories and event information subject to continuous state values.

When a state event has occurred the continuous simulation phase is interrupted. A `s(t,obj,ei)` message containing the state event's simulation object reference `(obj)` and the state event index `(ei)` is then forwarded along the edges of the modular computing model to the referenced simulation object. That action manages the state event by calling its specific `delta_x_s` method and it re-schedules its next internal event time by calling its `ta` method. It follows that all coupled simulation objects along the `s` message path also re-schedule their next internal event time. The `root_coordinator` can now start a new continuous or a discrete simulation phase.

A discrete simulation phase is initiated when the current simulation time reaches the next event time by sending an `*` message to the outermost simulation object. The cycle of a discrete simulation phase is very similar to the classical DEVS simulation approach in [1] so, for clarity, we will only discuss some modifications.

(i) Coupled simulation objects transfer an `x` message dependent on the current structure state to the corresponding input ports of their subobjects and subsequently execute their own state transition function `delta_x_s`.

(ii) Coupled simulation objects pass an `*` message to the subordinated simulation object planned for the next internal event and/or call their specific structure state transition function `delta_int` (if the current simulation time is equal to their time value in the `tnextC` variable). Simultaneous internal events inclusive structure events are prioritised by the object specific `select` method.

(iii) When structural changes occur, a recursive `z` and `i` message is sent to the outermost simulation object to reconfigure the reference vectors of `root_coordinator` and to initialize recently inserted simulation objects.

4 COMBINATION WITH OTHER COMPUTING METHODS

The MatlabDSDEVS-hybrid toolbox is fully compatible with the Matlab-environment and is therefore able to interact with other computing methods. This section identifies the benefits of integration and reviews how advantage can be gained from other methods. It is not intended to provide a detailed discussion of modeling and simulation. For an example of a hybrid and variable-structure engineering application using the MatlabDSDEVS-hybrid toolbox see [4].

Two common problems in simulation experiments are monte carlo studies for stochastic systems and parameter optimisation. As a consequence experimental techniques are provided in most commercial simulation packages. However, such experiments are often runtime heavy. Although such experiments offer significant potential for parallelisation with an almost linear speed up, commercial simulation packages cannot perform experiments using

parallel computing methods. In contrast special Matlab toolboxes provide user-friendly distributed and parallel computing methods. The first of these was the DP-toolbox published in 1995 [12][*].

The following example provides realistic demonstration of how computation methods can be easily combined. The example is taken from a series on comparisons of simulation software featured in the journal Simulation News Europe (SNE) [15]. The challenge addresses the modeling, simulation and optimisation of restaurant business dynamics and includes an opportunity for dynamic structure modeling. Although not an engineering problem, it provides an effective way of testing and evaluating the performance and features of the MatlabDSDEVS-hybrid toolbox.

The simulation model represents the dynamics of an area with a fixed number of people and a dynamically changing number of restaurants. A restaurant closes or opens depending on its profit in a certain time span and some probability values. A restaurant's profit is influenced by the tax rate considerably. One experiment is to maximize the government tax income by varying the tax rate for the restaurants. The system has to be simulated for 5 years and 50 simulation runs are necessary to achieve reliable average results.

Initially a classical solution for a single computer is developed. It contains of three parts: *(i)* the simulation model `MODEL`, *(ii)* the optimisation objective function `objFcn` and *(iii)* the interactive experiment execution commands. The following code shows the complete implementation of the objective function and all interactive execution commands.

objective function in file objFcn.m

```
1 value = function objFcn(taxRate)
2 global seedMat tfinal
3 taxIncome = zeros(50,1);
4  for i=1:50
5    taxIncome(i)=devs_start('MODEL',tfinal,…
                        seedMat(i,:),taxRate);
6 value = (-1)*mean(taxIncome);
```

interactive experiment execution

```
>>global seedMat tfinal
>>tfinal = 5*365;
>>seedMat= [1:50;51:100;101:150;151:200]';
>>[taxRate,meanTaxIncome]=fminbnd(@objFcn,0)
```

The *experiment execution* starts with a declaration of two global variables. The `tfinal` variable is initialized with the simulation final time and the `seedMat` variable is defined as a matrix with 50 rows and four columns. Each row stores the random number generator-IDs for one simulation run. Finally, one of Matlab's numerical optimisation algorithms is called and the objective function pointer `@obj_fcn` and a start value `0` for the optimisation parameter `taxRate` are passed. The optimisation method delivers the optimal tax rate and average tax income for the optimal parameter as result values.

Objective function takes the current optimisation parameter value in `taxRate` as input and delivers the objective function `value` as output. The global variables `seedMat` and `tfinal` are declared. In the third line a result vector `taxIncome` with 50 elements is initialized. Subsequently 50 simulation runs are performed in a for-loop (line 4 & 5). The MatlabDSDEVS-hybrids's function `devs_start` generates a `root_coordinator` object, calls its `start` method and passes the root_model_name `'MODEL'`, the `tfinal` value and one row of the matrix `seedMat` together with the current tax rate value as simulation model input parameters. Each simulation run delivers the accumulated tax income as output value. In the sixth line, the mathematical objective function is coded. It determines the average tax income and multiplies it by minus one because the numerical optimisation method implements a minimisation algorithm.

As stated such experiments are often runtime heavy and interactive program execution in SCEs is slower than the execution speed of compiled program code. However, we argue that such problems can be conveniently solved using parallel computing methods within SCEs. The following code shows the complete parallel implementation of the objective function using the DP-toolbox [12]. The *interactive execution commands* are the same as for the sequential program above.

parallel objective function in file objFcn.m

```
1 value = function objFcn(taxRate)
2   global seedMat tfinal
3   taxIncome = dpfeval(@devs_start,'MODEL',…
                    tfinal,seedMat,taxRate);
4   value = (-1)*mean(taxIncome);
```

The heart of the *parallel objective function* implementation is the vectorial RPC-function (Remote Procedure Call) `dpfeval`, introduced theoretically in [14]. It initiates parallel simulation runs using function pointer `@devs_start`. All other function arguments are passed to the `devs_start` function and evaluated as described by the non-parallel implementation. The number of programs executed in parallel depends on the number of available processors and the possible parallelisation degree of the problem. Both conditions are examined by the `dpfeval` function. In this case the extent of problem dependent parallelisation is determined by the function argument `seedMat`. This is the only non-scalar parameter. Therefore, its dimension is implicitly used as maximal parallelisation limit. The value of the result vector `taxIncome` is also defined implicitly. Runtime experiments on a nine-node computer cluster proved the prediction of approximate

[*] Since 2004 MathWorks provides an own toolbox, called Distributed Computing Toolbox [13].

linear speedup. This is not surprising as the ratio of communication to computation time is very small.

Another significant example for the combination of computing methods in SCEs is published in [9]. In this application a robot cell is controlled using a simulation model nand input data is generated from camera signals processed by Matlab's image processing algorithms.

5 CONCLUSION

We analyzed why the DEVS theory is relatively unknown in the broad engineering community and recognized the absence of a DEVS-based software implementation for engineering tools as a key reason. The development of a DEVS-based toolbox for hybrid and variable structure systems in the Matlab environment provides small contribution to the solution. The toolbox is still a development prototype consequently it is not yet an alternative for solving standard engineering problems. Nevertheless it is a suitable tool for teaching and research.

From a research perspective the DEVS-based toolbox's underlying modeling approach supports all known concepts of structure variability at the coupled system level and its simulation algorithms allow the computation of hybrid variable structure systems using Matlab's high performance integration methods. In addition the work has indicated that there are benefits in its use with other SCE computational methods such as optimisation and parallel computing.

The research has proved that the realisation of a DEVS toolbox in the Matlab environment is possible and useful. Currently implementation is not a trivial task as some programming features differ markedly from the general object oriented programming approach. A new release of an improved class concept has been announced and this development will be investigated in terms of its suitability for realising our DEVS approach.

Currently there seems to be no way to implement a toolbox for variable structure systems within the Matlab Simulink/Stateflow simulation environment. The next step in the research is to pursue this problem and develop a means to realise a static-structure DEVS toolbox in this graphical simulation environment.

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C16 Restaurant Business Dynamics – A MatlabDEVS based Approach

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Simulator: The MatlabDEVS Toolbox is a DEVS Simulator realized as an object oriented Matlab Toolbox. With the usage of Matlab the simulator shares all advantages and disadvantages of this well known and widely used SCE, a quite large basis of toolboxes, easy programming but also performance limitations because of the interpretive work. The toolbox implements to the greatest possible extent the Abstract Simulator introduced by Zeigler [*Theory of Modelling and Simulation*. Wiley-Interscience, Academic Press, 2000]. It was extended by port definitions and the capabilities to simulate dynamic structures after the formalism introduced by Pawletta et.al. [*A DEVS Based Approach for Modeling and Simulation of Hybrid Variable Structure Systems* Lect. Notes in Control & Informat. Sciences No. 279, pages 107-129, Springer]

Model: The model is implemented as a structure variable coupled DEVS model `MODEL`. This coupled model contains the following atomic models:

- two generators `gen_people gen_week`
  - one for the people going out to eat
  - another to force the calculation at the end of a week
- a model `switch` to choose a restaurant for a person from the list of possibilities
- a varying number of `restaurant` models (after initialisation 30, at the end of each week the number can change)

Figure 1 shows a graphical representation of the model *MODEL* after some weeks of simulation. Through the usage of a Dynamic Structure instead of an ordinary DEVS model the Real World structure is always mapped in a one to one manner. The simulator needs ca 2300s to simulate 10 years, with a dependency on the number of restaurants.

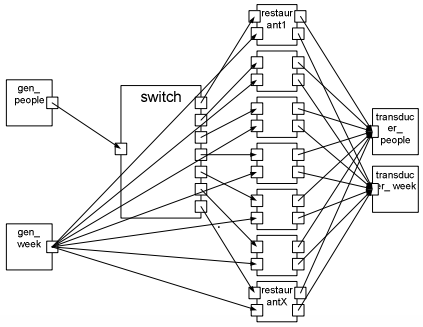

Figure 2 Representation of *MODEL*

Task a: Time Domain Analysis: The warm up period is finished after ca 30 weeks. Figure 2 shows the development of the mean number of restaurants over a simulation time of 10 years and 50 runs. Table 1 shows the result after 5 years.

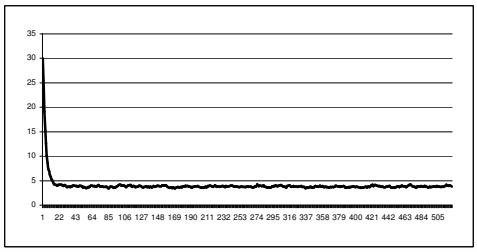

Figure 3: Development of mean number of restaurant in 10 year simulation time

Mean	4.24	Min	3.42
Variance	0.026	Max	4.2
Deviation	0.129		

Table 1: Results after 5 years

Task b: Tax Income Maximisation: It is possible to use the built-in Matlab optimisation functionality. In this case the *fminbnd* method is suitable. It determined the best tax rate at 39.23%. Figure 3 shows the mean tax income in the tax range from 1% to 99%

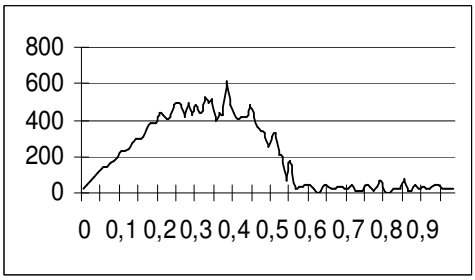

Figure 1: Mean tax income

Task c: Restaurants' Revenue Analysis: The simulation with a variable parameter k didn't have an obvious maximum. The results, shown in table 1 and fig 4, have two very close maxima with a difference of only 2.2%.

0	0
0,5	48,8
1	120,8
1,5	82,4
2	181,6
2,5	51,2
3	121,6
3,5	23,2
4	116
4,5	76,8
5	177,6
5,5	116,8
6	118

Table 2: Restaurant revenues with variable k

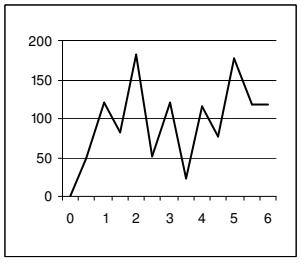

Figure 4: Restaurant revenues with variable k

C16 Classification: Dynamic Structure DEVS implemented as a Matlab Toolbox