Sönke Duckwitz, Andreas Petz, Christopher M. Schlick

Modelling and Simulation of Knowledge-Intensive Service Systems with Design Structure Matrices

Especially in highly developed, technology-oriented countries like Germany, knowledge-intensive services contribute significantly to prosperity and growth. Existing methods and tools for managing knowledge-intensive services rarely live up to the fast-moving demands and complex interactions. This is especially due to specific features of these services such as customer integration, uncertainties or the high degree of novelty. With regard to these requirements, new methods and tools are needed in order to analyse and model such service systems. Design Structure Matrices (DSM) are a promising method for modelling weakly-structured service processes. Additionally, they enable the integration of static and dynamic features. Using a process simulation approach the service model is transformed into a discrete event simulation, thereby allowing a holistic analysis and assessment. This approach supports service managers in making well-founded decisions, even in complex situations and under uncertainty. In a case-study, an excerpt from a high-tech based service of a chemical plant development, the modelling according to the DSM-methodology and exemplary results of the simulation are presented and discussed.

1 Introduction and motivation

The evolution to a knowledge society is confirmed particularly by an increasing share of services in gross value added and employment of highly skilled employees within the tertiary sector in Germany (currently over 70%) (IDW 2013). Faster innovation cycles and globalization bring along an increasing competitive pressure for companies, which leads them to use services not only for a differentiation of their service portfolio but also to develop new business models upon this. In order to remain competitive in the market, service companies have to improve continuously and provide efficient but also effective services. Compared to manufacturing industry and due to the specific characteristics of knowledge-intensive services, well-established methods and tools for service management hardly exist. This paper aims at introducing a modelling and simulation method for planning support of knowledge-intensive service systems. The novel method considers the specific conditions of the services, which are mainly provided in the form of projects. For the purpose of model construction, a systematic approach is recommended (VDI 2010). In section 2 the object of investigation is specified and abstracted in order to develop a model of the service system. The current state of research with regard to the requirements for modelling service systems and relevant modelling languages as well as existing service simulation approaches are presented in section 3. Section 4 introduces the DSM method, DSM-based simulation approaches and presents a DSM based modelling approach of knowledge-intensive high-tech services. Furthermore, a simulation concept for the planning of services is presented. The results of a case-study, performed in the chemical engineering industry in Germany, are presented in section 5 proving the practicality of the developed approach.

2 Knowledge-Intensive Services

No universal definition of services exists due to the very heterogeneous character of the service portfolio. Instead, a differentiation is made between different kinds of services, by highlighting their specific characteristics. Approaches for itemizing service-examples or a pure differentiation from manufacturing are too vague with respect to a scientific analysis (Corsten and Gössinger 2007; Maleri and Frietzsche 2008; Meffert and Bruhn 2012). In particular, this is attributable to an arbitrary and ambiguous differentiation of the inspection-perimeter.

2.1 Service Definition Based on Constitutive Characteristics

A widely used approach to specify service systems is based on Donabedian (1980) and Hilke (1989). According to these authors, service systems can be assessed from three different perspectives, the potential-dimension, the process-dimension and the outcome-dimension.

1. The potential-dimension represents the ability and willingness of the service provider to provide a certain service.
2. The process-dimension features the synchronicity of providing and consuming the service. A unique characteristic is the customer-integration, or rather the customer-specific contribution in terms of input-factors.
3. The outcome-dimension is marked by the perceived effects of the service outcome for the customer and the service provider.

Specific characteristics of services can be assigned to these three dimensions, also known acronymously as **IHIP**. Unlike products, services are immaterial (**Intangibility**), since they are based on service promise. Due to the contribution of the customers in the service delivery the service is customized (**Heterogeneity**). The contact, or rather the factor or information exchange with the customers is prerequisite (**Inseparability**). From a procedural and temporal perspective, the act of service delivery is elusive and not storable. Unused service is discharged (**Perishability**). (Corsten and Gössinger 2007; Fitzsimmons and Fitzsimmons 2011; Maleri and Frietzsche 2008; Möller 2008)

This specification is necessary; however, it is not sufficient for an advanced operative analysis. Narrowing the field of discourse relies on the concentration on knowledge-intensive services. Especially in developed, technology intensive countries like Germany, engineering-services, among others, play an important role. This is because technology-oriented services contribute to keeping and expanding innovation and competitiveness.

2.2 Knowledge-intensive services

Depending on the proportion of highly qualified persons with tertiary education, services are differentiated into knowledge-intensive and less knowledge-intensive services (Eurostat 2013). According to Götzfried (2005) knowledge-intensive service can further be subdivided into four different groups:

1. High-tech based services like data processing, research and development,
2. Financial services,
3. Knowlegde-intensive market-driven services like shipping, aviation, provision of services mainly for companies (B2B),
4. Knowlege-intensive services like healthcare, veterinary services and social services.

This classification is suitable especially for the comparison of economic sectors and macroeconomic indicators from an economic perspective. For analysing and designing work processes on an operational level the classification is too generic, but still provides a foundation for a more detailed reflection.

A common typology differentiates services according to their degree of complexity and interaction. This segmentation of services is based on an empirical investigation by Fähnrich et al. (1999). The study results show that knowledge-intensive services are characterised by a high intensity of contacts (customer integration) as well as a high rate of variant diversity (degree of customization) and thus show a high level of complexity (Baumgärtner and Bienzeisler 2006; Fähnrich et al. 1999). The immateriality of services implies an information asymmetry between the customer and the service provider (Meffert and Bruhn 2012). This leads to a mutually induced uncertainty in the evaluation of the service performance and in the behavior of the actors. As a consequence of these uncertainties and in combination with the process-oriented character of services, predictions of future states of the service process can only be made with a high degree of inaccuracy (Gausemeier et al. 1996).

Following the mentioned definitions and limitations, knowledge-intensive services are characterised by a high degree of individuality, customer integration, and uncertainty regarding future states. These specific characteristics of services are also applicable to project environments. The nature of project novelty and the uniqueness of conditions as well as a high degree of complexity (Bea et al. 2011; DIN 2009) enable the possibility to transfer the definitions of complexity from project management or systems theory to knowledge-intensive services.

Complexity of a system can be described based on the following attributes: number, diversity of elements and relations between the elements as well as the variability of the process course (Ulrich and Probst 1995). For very complex systems, these features are strongly pronounced. Statements about future states are not possible, as the system develops a certain momentum. Nevertheless, experts disposed with a corresponding practical knowledge are able to subjectively estimate probabilities of occurrence of events. Due to the strong interactions between the service elements, predictions about the effects of events are limited and only possible under highly simplified assumptions. In practice, this can lead to wrong decisions or even significant risks for the service company. A computer-based simulation can provide a considerable contribution to meet the challenges of complexity in knowledge-intensive services.

3 Opportunities and Limitations of Modelling and Simulation of Knowledge-Intensive Service Systems

According to Stachowiak (1973), a model should be specified in terms of three properties:

1. Property of mapping: A model is a representation of a natural or artificial original. In the present case, the model will be mapped by knowledge-intensive services.
2. Property of reduction: Only those attributes seeming relevant to their model construction should be used. In this case, the constitutive properties and features of complex systems will be considered.
3. Property of pragmatism: Models are constructed to fulfil a specific function. With regard to the simulation, the focus lies on the prospective analysis of dynamic service processes by key performance indicators (KPI).

The derivation of requirements for the modelling of knowledge-intensive services is conducted according to a basic model of knowledge-intensive service systems (see Figure 1), influenced by the work of Browning et al. (2006). In this model, six critical domains of a service are distinguished: 1) the customer demand, 2) input factors from both, the service provider and the customer, 3) human resources from the service provider as well as the customer (performing the service activities), 4) the service process system (activities performed in close cooperation by the service provider and the service customer), 5) the outcome system representing the service product, and 6) the goal system of the service provider as well as the service customer.

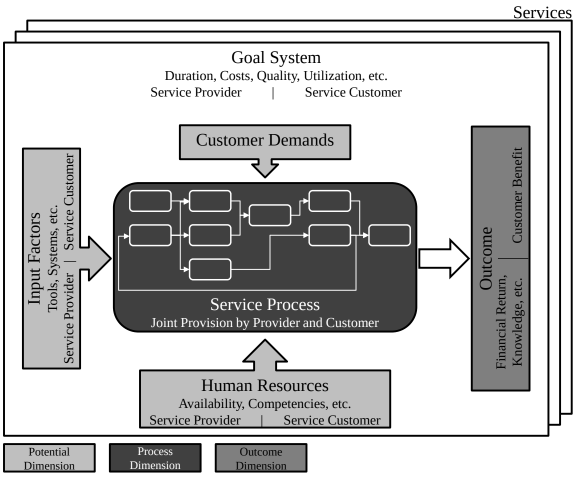

Figure 1: Basic model of a knowledge-intensive service system

Against this background the identified characteristics of knowledge-intensive services are formulated as requirements concerning a suitable modelling language and are assigned to the constitutive dimensions of services. Furthermore, relevant (semi-)formal modelling languages are considered that can be converted into a simulation-ready service model.

3.1 Requirements for the Modelling of Knowledge-Intensive Services

The requirements for the modelling of knowledge-intensive services can be derived from the three dimensional-character of these service processes.

Potential-Dimension

Knowledge-intensive services are personnel intensive work processes in which additional input factors such as tools and equipment only play a minor role and are often available without restriction. Following Bruhn and Blockus (2011) and Nielen et al. (Towards a modelling of knowledge-based services: Development of a meta model for the evaluation of process modelling languages) as well as the presented characteristics of complex systems, the number, variety and variability of involved actors in the provision of services as well as the information and communication processes represent a decisive factor for the service performance. This leads to the requirement that working persons with their different characteristics as well as the information and control flows between the tasks have to be modelled with the aim of mapping the organisational structure as a whole. Only the modelling of the whole system with its essential characteristics allows the measurement of the performance of the service potential.

Process-Dimension

The process perspective is the central dimension of the provision of knowledge-intensive services. From this perspective, the service is cooperatively provided by the working persons by task processing. Working persons are thereby assigned to tasks with the aim to generate a useful and beneficial solution for and with the customer. The challenge in modelling is to combine the different domains and often even opposed perspectives. A suitable modelling language should thus be able to merge a static and a dynamic perspective. The close cooperation of different actors and the often required shortening of the development time by a parallelization of tasks require a modelling language that can also map weakly-structured work processes (Kausch 2010).

Furthermore, knowledge-intensive services are often subject to changes in the requirements of the customer or iterations in the process of service provision due to deviations from the expected results. Work processes with a high number of interdependent tasks lead to iteration, which in turn cause additional time required for the project processing (Gärtner 2011). Since this effort can significantly affect the performance indicators, iterations should be considered in the service model.

Outcome-Dimension

In the majority of cases, the result of a knowledge-intensive service is a technical solution, a method or a procedure (Davenport 1993). This output is generally provided in close collaboration between the service provider and the service customer and cannot be predicted with absolute certainty. The requirement for the modelling is to allow the consideration of uncertainties or probable characteristics of future states.

3.2 Modelling Languages

In software development and business process management, well known languages such as the Unified Modelling Language (UML), Business Process Model and Notation (BPMN) or the Event-Driven Process Chain (EPC) are used for process modelling. These partially standardized modelling languages have been developed to describe processes formally and to create reference models or to serve as a basis for discussion across different domains (e.g. requirement analysis, etc.). In practice, mostly academic approaches and tools exist that can transfer these modelling languages into a form suitable for simulation (List and Korherr 2006; Mendling and Nüttgens 2006). Additionally, the modelled processes and tasks have to be enriched by additional and especially quantifiable parameters (properties of the working persons, uncertainties, etc.). These special requirements (cooperative, weakly-structured work processes, etc.) are not satisfied by the mentioned modelling languages (Heß et al. 2013; List and Korherr 2006; Nielen et al. 2010; Preiß and Kaffenberger 2013).

Particularly in knowledge-intensive service processes with more than 80 tasks, graphical models become confusing and interactions and changes in the process flow cannot be visualized easily (Mendling et al. 2010). Mendling et al. (2010) recommend dividing graphical models with more than 50 tasks into smaller models which contradicts the aim of a global analysis and optimisation. Overall, the established modelling languages are not able to fully meet the specified requirements on modelling knowledge-intensive service systems.

3.3 Requirements for Simulation and Discussion of Existing Simulation Approaches

People are limited in detecting complex relationships (Gausemeier et al. 1996). By using process simulation, complex service systems can be analysed prospectively considering a multitude of specific relationships. In particular, during the planning of knowledge-intensive service systems, simulation enables, for example, a visualization of alternative service courses as well as the analytical calculation of certain performance indicators (time, cost, etc.). A simulation study results in service plan alternatives of a concrete services provision and can thus serve as a decision support system for the service planner. Similar to simulation methods in production and logistics, an increasing use of simulation approaches in the service sector can be observed.

The procedure of developing the service model and the simulation model shows some similarities but also differences between the application areas. These differences are based on the previously introduced characteristics of knowledge-intensive services. Due to the inherent uncertainties and the focus on the process, the use of a discrete-time simulation with stochastic input variables is considered suitable for the present scope.

On management level, influencing factors on the productivity of services and their complex interactions can be mapped and simulated by the Systems Dynamic methodology (Rannacher et al. 2013). However, due to the high level of abstraction, a detailed process analysis at workflow level cannot be performed.

Less knowledge-intensive services can be modelled by queuing models in a simplified manner. Queues form the structure of an operating system consisting of a server and a waiting room. Abstract objects and/or subjects (e.g. order, etc.) are "guided through" the system. Operating systems, such as supermarkets, airports or restaurants can thus be analysed validly (Laughery et al. 1998). Results of a queuing model simulation are typical indicators describing the steady state of the system, the server utilization, the queue length or the waiting time. A modelling and simulation environment for these types of systems is provided by the Petri net methodology. For the simulation of knowledge-intensive service processes, this approach is not suitable, because among others in addition to the allocation of resources the analysis of different network topologies (service provision paths) should be possible with relatively little effort. Furthermore, a process-oriented modelling of weakly-structured work processes can only be performed to a limited extent (Winkelmann 2007).

With regard to the numerical simulation of knowledge-intensive services, the Design Structure Matrix (DSM) provides an adequate, flexible and scalable modelling method that can be easily applied to a numerical analysis of the simulation results. A detailed consideration of this modelling method can be found in the following section.

4 Modelling and Simulation with Design Structure Matrices

An interesting and promising modelling approach was developed by (Steward 1981) in the context of product development processes. This matrix based modelling, the so called Design Structure Matrix (DSM), shows a good suitability for the modelling of knowledge-intensive service processes.

4.1 General Exposition of the DSM Approach

In addition to methods for measuring characteristics of the design based on information-theoretic quantities, a large body of literature has been published around the DSM (Steward 1981) as a dependency modeling technique supporting complexity management by focusing attention on the elements of a system and the dependencies through which they are related. Recent surveys can be found in the textbooks of Lindemann et al. (2009) or Eppinger and Browning (2012). Browning (2001) distinguishes two basic DSMs types: static and time-based. Static DSMs represent either product components or teams in an organisation existing simultaneously. Time-based DSMs either represent dynamic activities indicating precedence relationships or design parameters that change as a function of time. Generated static DSMs are usually analysed for structural characteristics or by clustering algorithms (e.g. Rogers et al. (2006)), whilst time-based DSMs are typically used to optimize workflows based on sequencing, tearing and banding algorithms (e.g. Gebala and Eppinger (1991); Maurer (2007)). Kreimeyer and Lindemann (2011) review and discuss a comprehensive set of metrics that can be applied to assess the structure of engineering design processes encoded by DSMs (and other forms).

The method was continuously improved so that the DSM is now widely used in different domains for the optimisation of products, processes and organisation (Eppinger and Browning 2012).

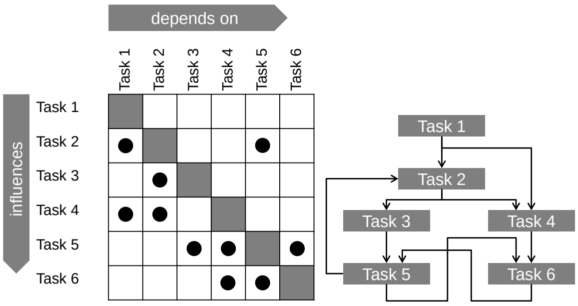

Figure 2: Depiction of dependencies between tasks in a DSM (left) and the corresponding process diagram (right) according to Gärtner (2011)

Figure 2 depicts a time-based DSM with six tasks. Markers within the matrix qualitatively indicate the dependencies between the tasks, exemplarily shown as a flowchart on the right figure. Forward directed dependencies are marked below the main diagonal of the matrix, backward directed dependencies are depicted above the main diagonal (IR/FAD convention according to Eppinger and Browning (2012)). In this way, iterations as typical alteration-loops and their effects are considered. The entries in the matrices allow the modelling of different process-strategies: sequential processing (task 1-2), parallel (independent) processing (task 3-4), or coupled (dependent) processing (task 5-6). Additionally, by replacing the markers in the matrix with real numbers (e.g. stage of processing) the modelling of task overlapping becomes possible.

To combine two different systems (e.g. product, process, organisation) the concept of Domain Mapping Matrices (DMM) was developed (Danilovic and Borjesson 2001). A DMM is able to represent the influence of the i elements of one system on the j elements of another system in the form of an i x j matrix.

First approaches for determining and optimising the duration of the product development process through a DSM were made by Smith and Eppinger (1997). Compared to other methods, the DSM also enables a depiction of asymmetrical information dependencies and weakly-structured working processes (Smith and Eppinger 1997). In addition, the matrix representation allows a scalable description and a numerical analysis of complex dependencies.

4.2 DSM-based Simulation Approaches

Different DSM-based simulation approaches were developed to simulate product development processes in recent years. Following the work of Smith and Eppinger (1997) more comprehensive simulation models were developed by Browning and Eppinger (2000), Yassine et al. (Do-it-rightfirst-time (DRFT) approach to DSM restructuring), Yassine and Browning (2002), Cho and Eppinger (2001), and Lévárdy and Browning (2009). With the focus on the determination of an optimal processing sequence of tasks, simulation and optimisation approaches were developed by Zhuang and Yassine (Task scheduling of parallel development projects using genetic algorithms), Huang and Gu (2006), and Abdelsalam and Bao (2006). In addition to these DSM based models, also simulation models on the basis of the Work Transformation Matrix (WTM), a numerical form of a fully occupied DSM including two types of information (degree of dependency between the elements resulting in iteration induced rework as well as the basic duration of the task processing), are existing (Cronemyr et al. (2001); Huberman and Wilkinson (2005); Schlick et al. (2012)). A comprehensive overview of DSM-based simulation approaches is given by Gärtner (2011).

Weaknesses of the existing simulation approaches are mainly conceptual deficits concerning the connection of the process model with the personnel resources, required for the task processing, and the lack of an learning effect regarding the iteration probabilities.

The simulation model presented in this paper is based on an approach of Gärtner (2011) that was designed for new development projects in the automotive industry. Here the modelling is conducted with a Microsoft-Excel Worksheet. The simulation algorithm was developed as a Monte-Carlo simulation and prototypically implemented in Matlab.

4.3 Modelling of Knowledge-Intensive Services with DSM

The present concept for modelling knowledge-intensive services uses the DSM as well as the DMM concepts. This is necessary in order to connect the static and dynamic domains with each other. The perspectives to be integrated are oriented towards the specification of services according to the three different dimensions (Donabedian 1980; Hilke 1989). In addition to these three dimensions, uncertainty is considered in more detail as a fourth central characteristic of knowledge-intensive services.

		Resource-Task mapping				Workflow definition						Key performance indicators			
		Role 1	Role 2	Role 3	Role 4	Task 1	Task 2	Task 3	Task 4	Task 5	Task 6	Duration [TU]	Costs [MU]	Effort [FTE]	etc.
Process-dimension	Task 1	1										10	45	44	…
	Task 2					0,2				1		5	78	66	…
	Task 3			4			0,8					3	52	23	…
	Task 4				2	1	0,5					4	98	11	…
	Task 5		3					1	0,5		1	7	4	2	…
	Task 6				1				1	1		8	56	78	…
Potential-dimension	Employee 1	0,7										…	…	…	…
	Employee 2			0,8	0,5							…	…	…	…
	Employee 3		0,6									…	…	…	…

Figure 3: Exemplary depiction of different domains of a knowledge-intensive service in DMM

Figure 3 shows an example of the mutual dependencies between the elements of the service system in the form of DMMs. The potential-dimension is addressed in a static DMM through the definition of the organisational structure as well as through the employees involved in service delivery. As the central dimension of service provision, the process-dimension is depicted by a dynamic DSM with n x n tasks. The interplay between process, organisation and employees results in a possible form of a service plan. This plan has specific properties that are covered in the outcome-dimension. This includes the classical performance indicators like duration, costs, etc.

Potential-Dimension

In the potential-dimension, different types of resources can be represented. Due to the characteristics of knowledge-intensive service systems, in this case human resources are in the focus. This is facilitated especially by the integrated role concept. A role is a person independent organisational unit and is responsible for the execution of one or more tasks (Schlick et al. 2010). The role contains a description of the working profile (rights and obligations) and enables a flexible and neutral assignment of persons to tasks (e.g. service manager, technical planner, etc.) (DIN 2009).

In addition to the abstract roles, the specific employees are modelled in the potential-dimension as well. Thereby, only those characteristics of the employees are considered that do influence the processing effort basically. These crucial characteristics were identified by the authors using an explorative study (Petz et al. 2012): qualification, availability (working hours, workload), and monetary costs (cost rate). In Figure 3, the upper left matrix combines the resources' roles with the tasks of the service process. The values in the Task/Role DMM represent the number of employees from a specific role needed to process the task successfully. The lower left Employee/Role DMM shows the operationalized qualification of the employees for the different roles on a scale from 0 (unqualified) to 1 (perfectly qualified). For reasons of clarity, the presentations of the availability of the employees and the monetary costs are not included in Figure 3.

Process-Dimension

The process-dimension depicts the process organisation of the service system. It consists of the different tasks required for service provision as well as their dependencies.

A task is the lowest unit of a process. In the presented service model a normalized effort for execution is ascribed to each task. Here, the normalized effort can be defined as the effort that an employee with qualification 1 has to invest in order to process the task completely. Employees are not directly assigned to a task, but rather indirectly via the role concept. During this assignment of employees to tasks, besides the attribution to the required role, the qualification of the person is also considered.

The dependencies between the tasks are modelled in a square matrix, as illustrated in Figure 3 in the upper middle DSM. A numerical matrix is assumed so that besides the possibility considering the modulation of sequential, parallel and coupled tasks it is also possible to model overlapping tasks and iterations. In Figure 3, the values below the diagonal depict the required degree of completion of the predecessor task whereas the values above of the diagonal indicate the probability of the occurrence of iterations. For example, in order to start task 2, task 1 has to be 20% finished. After task 5, task 2 will be repeated with a probability of 100%. In accordance to the concurrent engineering concept, the overlapped processing of tasks as well as frequent iterations can already be considered during the initial service planning phase. The complete description of iterations requires the consideration of iteration-frequencies. This can be regarded as the degree of learning of the system since it controls the number of iterations (Gärtner 2011). In the model this can be parameterized by the decrease of the iteration probability. For reasons of readability, the Task/Task DSM in Figure 3 is a simplified version of the multidimensional matrix used in the implemented simulation model. Furthermore, the communication effort is not depicted in Figure 3, but it is considered during simulation. Communication effort is quantified based on the number of internal and external interfaces (e.g. consultation of experts, discussions with the service customer, etc.).

In addition to the iteration feature, the constitutive element *customer influence* on service provision is also taken into account. The concept of a so-called tolerated incompleteness considers different customer types by taking the requirements regarding the demanded degree of quality into account. Less demanding customers, e.g. with regard to the completeness of the documentation, induce less effort, while particularly strict customers create a higher effort for a customer-accepted task processing.

Outcome-Dimension

In the outcome-dimension the key performance indicators suitable for an evaluation of different service organisations are computed (see upper right Task/KPI DMM in Figure 3). The central element is the effort of the service provision. This performance indicator reflects the crucial characteristics of a knowledge-intensive service process, such as tasks interrelations or additional effort due to task-overlapping induced rework. The effort is furthermore influenced by the qualification of the assigned employees and by the level of customers' requirements. The effort directly influences additional performance indicators, like costs or personnel utilization.

The simultaneously considered static and dynamic characteristics of the underlying service model allow an observation of the effects of specific influencing parameters on the service performance.

The different, alternative service plans resulting from a simulation study serve as a basis for different possibilities of service process visualization. The plans can furthermore be compared based on the specific performance indicators. A detailed performance evaluation can be performed in accordance to a given service level agreement or service specification and requirements.

The use of a dynamic simulation system enables the extension of the system with a multicriteria optimisation system.

Uncertainty

The prospective estimation of efforts and the prediction of the customer's influence on the task processing is rather challenging as many interdependencies in conjunction with variability exist. To deal with uncertainty in the development of the service model, the effort of a task is specified by a continuous-type random variable with a beta-distribution. For the construction of this distribution, three estimates are required: the optimistic, the pessimistic and the most likely value for the normalized effort (according to an employee with a qualification level of 1.0). Additional parameters have to be specified to represent other characteristics of task processing in knowledge-intensive service processes. In order to model the influence of the present customer, a minimum task duration as well as a reasonable degree of task incompleteness must be assigned to specific tasks. The task duration in each single simulation run is automatically computed by the simulation algorithm presented in section 3 according to the parameterization of the model.

4.4 Simulation Algorithm

A simplified simulation algorithm is depicted in Figure 4. The algorithm was implemented in Matlab, a software environment that was especially developed to deal with complex matrix calculations and offers a perfect environment for the prototypical realization of the simulation concept.

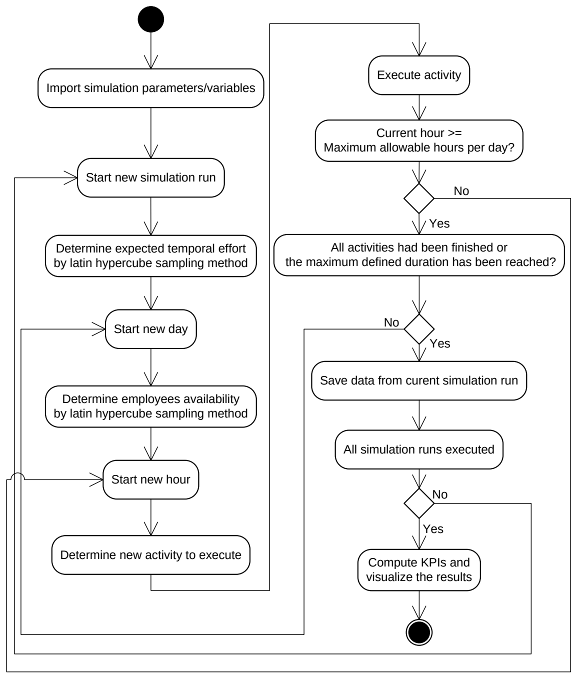

Figure 4: Process logic of the simplified simulation algorithm for the analyses of knowledge-intensive service systems with DSM

In a first step, tasks available for processing are identified. A task is activated for processing, once the required degree of completion of its predecessors is reached. This degree is specified in the process DSM (see Table 1). In the second step, employees are assigned to the activated tasks based on roles. The mapping of employees to the tasks can be performed in the simulation model by three different assignment policies concerning the suitability of the employee's qualification: a random assignment of the employees satisfying the qualification requirement of the task, a best fit assignment (in terms of the employee's qualification level for the required role) or an assignment in a predefined order.

After the assignment of the employees, the presumably needed effort for processing each task is computed. For each of the assigned employees, a partial effort is determined based on his or her qualification. Furthermore, additional effort is added due to task overlapping and the employees interaction quantified by supplementary communication and collaboration efforts. This communication and collaboration effort is quantified by the number of interfaces per employee involved, summed up and assigned to respective tasks.

The task can now be executed and the effort, the assigned employees need to complete the task, is reduced accordingly. Once a task is completed, iterations are considered. The probability of an iteration occurrence is taken into account and resulting iteration tasks are treated in the same way.

After the completion of all tasks, the data produced during the simulation run is stored, and the next simulation is started. A simulation study ends, when the predefined number of simulation runs is reached. At the end of each simulation study, the overall results are computed and visualized.

4.5 Visualization of Simulation Results

The performance of a simulation study results in a high amount of simulation data and different visualizations (see Figure 5). So, different Gantt-charts are produced, showing in detail the simulated course of the service process (upper left in Figure 5) or the required personnel deployment for service execution (upper right in Figure 5). Furthermore, occurrence frequency distributions are automatically visualized, for example concerning the combination of costs and durations (lower left

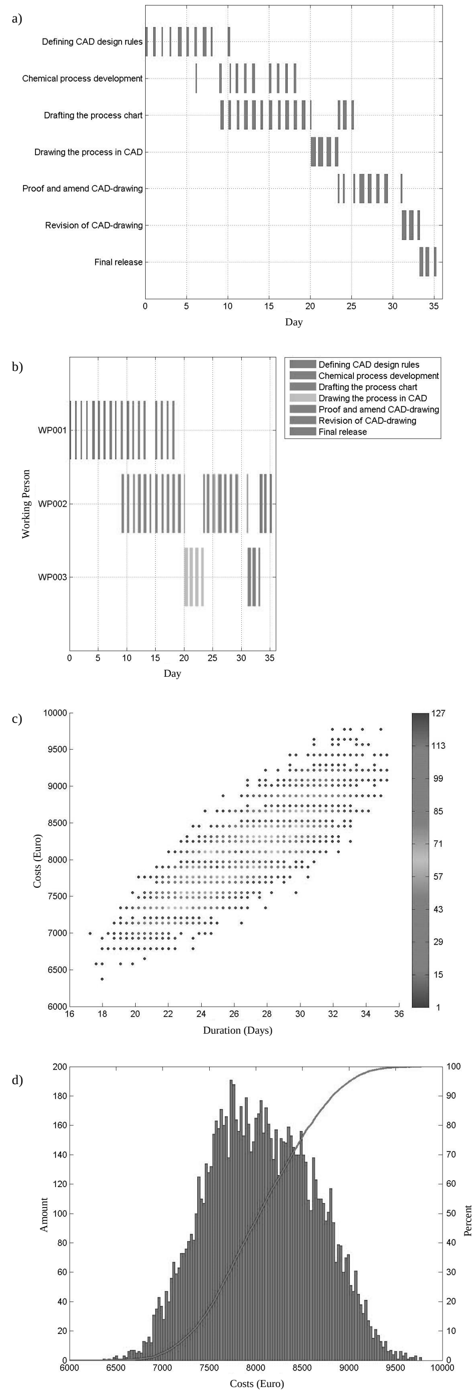

Figure 5: Exemplary visualization of simulation runs (a) Gantt-chart of the service process, b) Gantt-chart of employee deployment, c) frequency distribution of cost-duration combinations, d) frequency distribution of the costs)

in Figure 5) or the total costs of a service provision (lower right in Figure 5).

These visualizations of the simulation results play a crucial role in the evaluation of different service scenarios in an extensive simulation study. With the help of the simulation system, what-if-analyses supporting the planning of knowledge-intensive services can be performed (see Figure 6). To carry out a simulation study, first the service model has to be developed and the parameters have to be specified by a service expert. After the service modelling, simulation runs are made and the results are visualized. Based on the results, a service planner is enabled to define alternative scenarios, leading to an adjustment of the model parameters and thus resulting in new simulation runs and new simulation results. By performing the cycle depicted in Figure 6 the service planner can determine the optimal service organisation to meet the service's objectives.

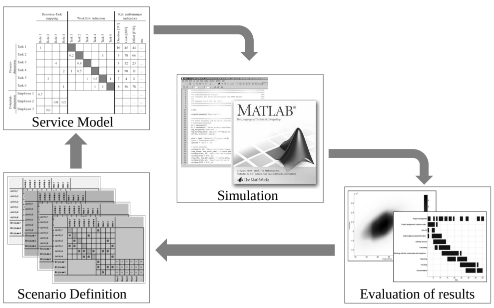

Figure 6: Simulation study cycle

5 Case-study

5.1 Service Scenarios

In order to evaluate the developed modelling and simulation system for knowledge-intensive service systems, a case-study was carried out. This study concentrates on the early phase of the development of a piping and instrumentation diagram (PID) in a German company, a popular high-tech engineering service in the chemical industry. The study considers the first seven tasks during the process design phase of a chemical plant development. First, CAD design parameters and design rules are defined by the project leader. This task serves as the starting point for the chemical process specification. Subsequently, a rough chemical process plan development is performed, followed by the creation of a detailed process layout using CAD-software. The finalized process layout has to be proved and commented. Following the amendments for modification, the CAD-drawing is revised and finally released.

To evaluate the possibilities of the modelling and simulation system, two different scenarios are considered. Each scenario represents a different service organisation for a service planner to choose between. The first scenario is characterised by an employee pool of two process engineers. The seven tasks have to be performed by these two employees. In the second scenario the two process engineers from the first scenario are assisted by a technical drafter. The case-study aims at revealing the differences between the two organisational designs in terms of overall service productivity.

5.2 Service Model and Parameters

Table 1 shows two parameter settings of the engineering process with the two different resource allocations. In the process DSM (square matrix on the left), task interrelations are modelled. Entries on the gray diagonal represent the estimates of the expected task effort of a full time equivalent employee with 1.0 qualification level. For example, considering the first task, one skilled employee has to work at least 4 hours to finish the task. Most likely he has to work 8 hours, in the worst case he has to work 16 hours to complete this task. Entries below the diagonal represent the conditions for task activation. In order to activate the second task, the first task has to reach a degree of completion of

Table 1: Integrated process model and structural model of the case-study

								Scenario 1			Scenario 2		
Task	1	2	3	4	5	6	7	E1	E2	E3	E1	E2	E3
1	4/8/16							R	C	X	R	C	X
2	0.7	6/8/12	0.1	0.2				R	C	X	R	C	X
3		0.1	14/20/25					X	R	X	X	R	X
4		0.7	1.0	8/10/12				C	R	X	C	C	R
5				1.0	4/8/10	0.5		C	R	X	C	R	C
6					1.0	3/5/6		C	R	X	C	C	R
7						1.0	2/4/5	C	R	X	C	R	C

1 - Defining CAD design rules
2 - Chemical process development
3 - Drafting the process chart
4 - Drawing the process in CAD
5 - Proof and amend CAD-drawing
6 - Revision of CAD-drawing
7 - Final release

Legend:
R - Responsible
C - Consulted
X - not assigned

70%. Entries above the diagonal represent iteration probabilities. The probability that the second task has to be iterated after the third task is completed is 10%.

The assignment of the employees is given by the intra-domain matrix on the right. Three different roles are considered: employee 1 (E1), a process engineer and the project leader, employee 2 (E2), the second process engineer and employee 3 (E3), a technical drafter. In this simplified case-study only one person is assigned to each role, thus the employee-role DMM becomes obsolete. An employee, who is responsible for the given task, has to ensure a sufficient task fulfilment. A consulted employee has to provide all necessary information to the responsible person. Due to the possibility of an overlapping processing of some tasks a rework effort of 0.3 from the current remaining effort is considered, once a task starts before all predecessors are completed.

The availability of the employee in the service scenario of this case-study is limited due to commitments in other service provisions and it is given by a three-point estimate. The project leader has most likely the availability of only 20% for this service (0.1-0.3; worst case - best case), the process engineer of 30% (0.2-0.4; worst case - best case) and the technical drafter of 40% (0.3-0.5; worst case - best case) per working day. The communication effort is considered by adding an additional effort of one hour per involved employee and week.

Furthermore, a reasonable incompleteness of task number three of 20% is assumed since the customer prefers the discussion of the developed PID on the basis of the CAD data.

5.3 Simulation results

Both organisational scenarios of the presented service process were simulated. For each condition 10,000 independent simulation runs were computed. The results of the key figures are presented in Table 2. For both scenarios the arithmetic means of the service duration, the overall effort and the total costs were computed. Furthermore the utilization of the working persons is computed and visualized in box-plot diagrams. The occurrence frequencies of equal cost-duration characteristics within the 10,000 simulation runs of each scenario are depicted in the cloud diagrams. Based on these results an evaluation of the two different service organisations can be performed. The results show that involving the additional technical drafter in the second scenario reduces the average service provision duration by two days. On the other hand, it becomes clear that, in turn, the overall effort and the total costs increase. One reason for this effect lies in a higher communication effort because of consultations between the three involved employees (see Figure 7).

The support of the technical drafter in the second scenario leads to a decreased utilization of the process engineer (see Figure 8).

Table 2: Results of the two simulated scenarios (SD: standard deviation)

Scenario 1 Without support of technical drafter		Scenario 2 Supported by technical drafter	
Average duration:	31 days (SD: 2.6)	Average duration:	29 days (SD: 2.7)
Average effort:	91 working hours (SD: 5.3)	Average effort:	103 working hours (SD: 5.9)
Average costs:	8,147 Euro (SD: 462)	Average costs:	8,823 Euro (SD: 503)

The relative capacity utilization in the first scenario is relatively high with a level of 65% and 78% respectively. The utilization of the project manager even increases in the second scenario, the relative utilization of the technical drafter is only 27%. This shows that the provided availability of the technical drafter is not necessary and allows the cooperation of the technical drafter in further services, without causing negative effects on the presented service excerpt.

Additionally, the second scenario has higher deviations of the duration, effort and costs. So, the first scenario is more robust (lower variance) regarding duration and costs, while exposing a higher risk of capacity unavailability due to high capacity utilization. The second scenario is far more flexible from the resource allocation point of view thus exposing higher variability in service delivery.

A service planner can now decide, based on this detailed information, which scenario is more promising in order to reach the service objectives.

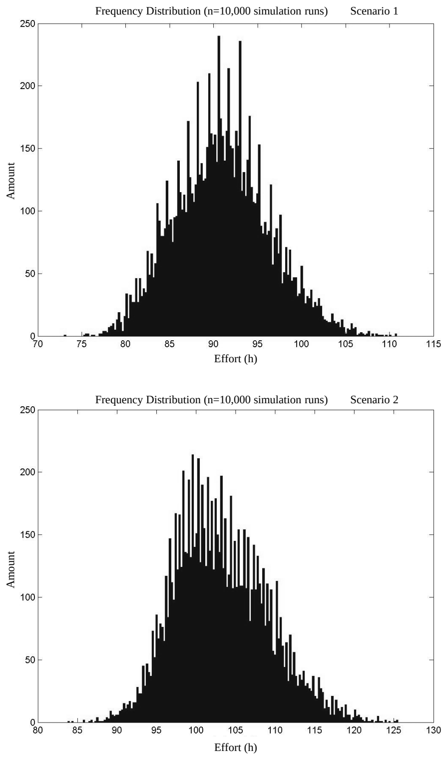

Figure 7: Simulated effort in working hours of scenario 1 (top) and scenario 2 (bottom)

6 Summary and Outlook

The paper shows how a method from the field of complex product development can be transferred to the modelling and simulation of knowledge-intensive services. The modelling of a high-tech based service was illustrated and discussed in the case-study based on an excerpt from a complex process plant development service. Performance indicators for the evaluation of different service scenarios were computed and can serve as supporting information for the service planner.

Future work will focus on the collection of additional applications of our industrial partners. The service model will be simulated to verify the underlying model and the simulation algorithm. In particular, sensitivity analyses will be conducted and evaluated. Moreover, it is planned to gradually expand the simulation model to incorporate a multi-criteria optimisation algorithm to enhance service managers decision support system. Thus, managers are empowered to develop and implement best practice service plans for knowledge-intensive service systems.

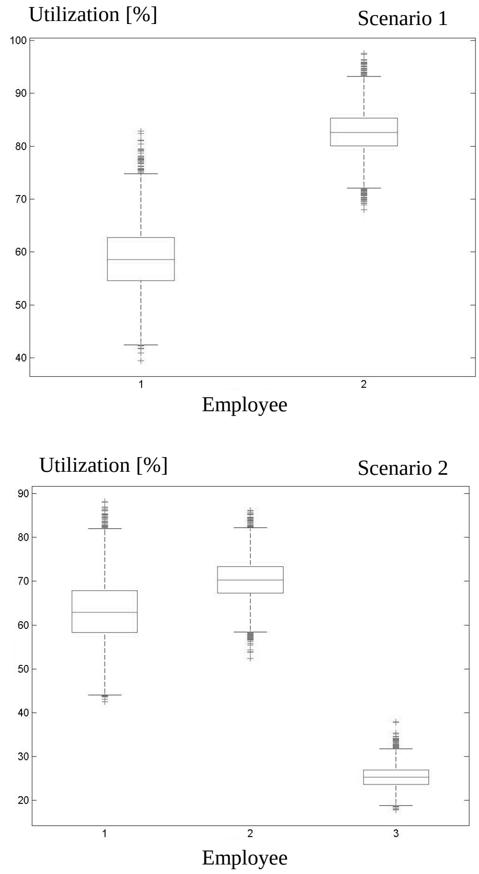

Figure 8: Employee utilization in scenario 1 (top) and scenario 2 (bottom)

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Sönke Duckwitz
Chair and Institute of Industrial Engineering and Ergonomics at RWTH Aachen University
Bergdriesch 27, 52062 Aachen, Germany
s.duckwitz@iaw.rwth-aachen.de

Andreas Petz
Chair and Institute of Industrial Engineering and Ergonomics at RWTH Aachen University
Bergdriesch 27, 52062 Aachen, Germany
a.petz@iaw.rwth-aachen.de

Christopher M. Schlick
Chair and Institute of Industrial Engineering and Ergonomics at RWTH Aachen University
Bergdriesch 27, 52062 Aachen, Germany
c.schlick@iaw.rwth-aachen.de