KEYWORDS Service simulation Service modeling Key performance indicators Design structure matrices

ABSTRACT

In developing and developed countries industrial, knowledge intensive services play an important role. Companies face problems in efficient and effective development and operation of new services because, among others, of their traditional, production-oriented systems and the characteristics of knowledge intensive services. A novel approach combining design structure matrices and discrete event simulation can help to improve knowledge intensive service systems development and delivery and to foster company's competitiveness. The paper presents the underlying models focusing on service specific characteristics along the potential, process and outcome dimension of the service systems composition. Structural characteristics are supplemented by considering specific dynamic behavior in complex systems like overlapping and iterations. In a case study in the chemical engineering industry the utility of the approach is evaluated. The results can be used to support development decisions as well as for identifying levers for improvement.

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MODELING AND SIMULATION OF SERVICE SYSTEMS
with Design Structure and Domain Mapping Matrices

1. Introduction

Companies can capture a large fraction of their overall benefit with services *(Koudal and Deloitte Research, 2006)*. For example, the costs for operation and upkeeping of industrial machines often account for up to 90 percent of the machine purchase costs. To exploit this revenue and profit potential, companies have to systematically build and expand their services.

Many companies are confronted with the problem that their implemented organizational structures and processes are not optimally designed for efficient development and provision of new services *(Rosenkranz, 2009)*. In particular, they often lack clear definitions of the provided services as well as distinct descriptions of service specifications, inherent service processes and needed resources. Furthermore, there are only a few practical methods and tools to assist the strategic and operative planning of service processes and to develop competencies and skills for efficient service provision design. Service engineering aims to extend engineering approaches and experiences as well as corresponding models, methods and tools developed for conventional product development to the area of services. Service engineering covers the systematic development and efficient design of services and service products using adequate models, methods and tools *(for an overview of the developments in service engineering, refer to Meyer et al. (2012))*. It provides an interface between conventional service science and engineering science. As the service sector becomes increasingly important, service engineering methods have the potential to support companies in the development of innovative and complex service models as well as stable and efficient service processes that are adequate and proportionate to minimize risks and the costs of service provision.

In connection with product development, matrix-based techniques are widely applied to analyze and manage complex systems. The Design Structure Matrix *(DSM)* supports engineers and project managers in modeling, visualizing and analyzing static as well as dynamic dependencies among the entities in complex, knowledge-intensive projects *(Steward, 1981)*. In a dynamic DSM, a product development or service provision process is decomposed into n distinct activities, which are entered as labels in the rows and columns of an n x n matrix. The values in a given cell indicate informational dependency or coupling between the corresponding activities, resulting in feed-forward control flows in the lower triangular matrix and feedback control flows in the upper triangular matrix. Hence, the strength of the DSM is its clear and compact representation, which allows it to consider iteration loops and mutual activity dependencies. Interactions, interdependencies and interfaces between entities in a complex system can be captured easily in a DSM.

Despite the methodological support of the DSM, product development project planning and corresponding resource management is an extremely complex task for project managers *(Pietras and Coury, 1994)*. Likewise, it is an equally complex task to find the optimal design of service provision and scheduling of service activities. The application of the DSM method in itself does not ensure appropriate consideration of certain precedence and resource constraints and optimal use of resources, customer satisfaction and the attainment of service targets in an acceptable period of time. Instead, innovative methods and tools like computer-aided simulation are considered to improve the design and scheduling of a complex service provision. Dynamic simulation approaches enable human schedulers to forecast the total period of a service provision as well as effects of changes to the design of a service provision. In combination with simulation approaches, dynamic DSM-based modeling can lead to a significantly better, more realistic design and planning of the service system.

Several dynamic simulation approaches have been developed which use DSMs to model interdependencies between project activities and simulate the information flow of planning processes with Marcov chains, discrete event simulation models or Monte-Carlo-simulation *(cf. Smith and Eppinger, 1997; Carrascosa et al., 1998; Baldwin et al., 1999)*. Further developments consider resource constraints in a multi-project environment, estimation of iteration probabilities and Petri-net simulation based on intra- and inter-activity DMMs *(cf. Yassine and Browning, 2002; Karniel and Reich, 2007)*. An interesting approach is the modeling of autonomous task scheduling behavior based on information relation matrices and agent-based product development process simulation *(Zhang et al., 2011)*.

This paper presents a novel modeling and simulation approach of service systems considering service specific characteristics described in section 2 and 3. The modeling and simulation concept grounds on an approach developed by Gaertner *(2011)* for new product development projects in the automotive industry.

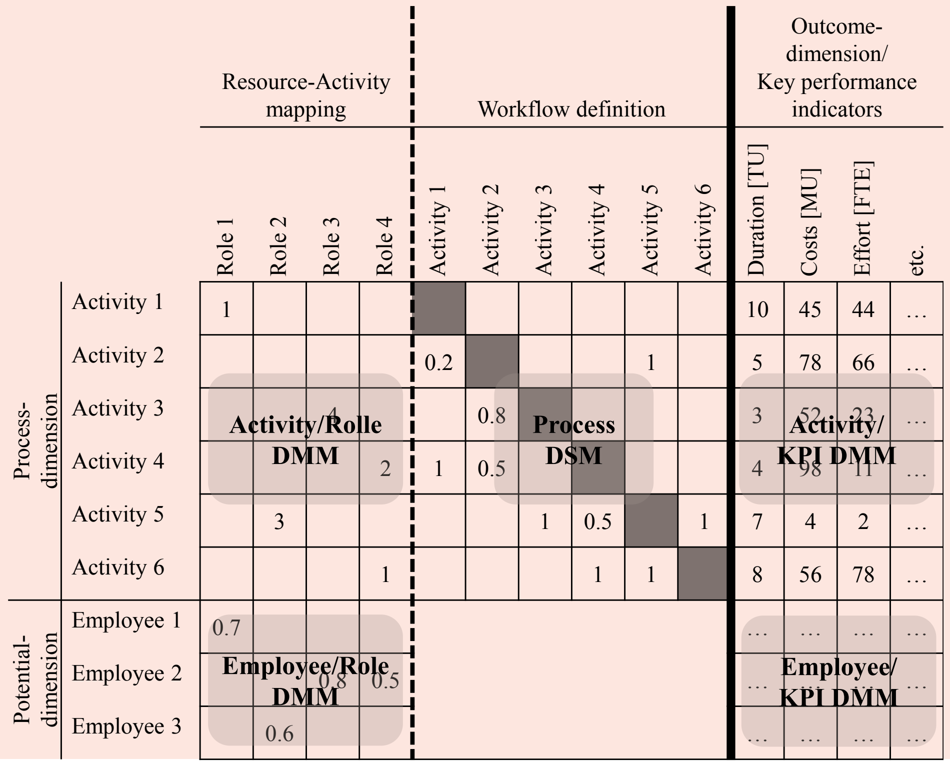


FIGURE 1. *Example of relationships between the considered service system elements*

2. Modeling of Service Systems

The modeling approach uses the service system definition by Donabedian *(1980)* and Hilke *(1989)*. Thus, a service system is specified and can be assessed from three different perspectives:

- Potential dimension: The service provider is willing and has the ability to provide the specified service. This potential is time and space dependent and perishable.
- Process dimension: Service provider and consumer interact for an individual service provision.
- Outcome dimension: The perceived effect of service provision.

Furthermore, according to Stachowiak *(1983)* and Banks *(1998)* a model should be built upon specific characteristics considering only the partial representation of the real system and focusing on relevant characteristics for the specific purpose of the study. For a comprehensive performance evaluation of the service system only essential characteristics are attributed to the service specific dimensions. The potential dimension comprises the organizational structure as well as human resources and their specific abilities and skills; the process dimension focuses on the process workflow and the task-resource assignment; finally, the outcome dimension focuses on the service systems overall outcomes quantified by key performance indicators.

In order to model the constructs and the interdependencies between the dimensions we use both intra-domain and inter-domain matrices *(see* **Figure 1***)*. The central dimension is the process dimension as it represents the dynamic part of the service. This dimension is influenced by the potential dimension and affects the outcome dimension.

2.1 Service Potential Dimension

The simulation model considers only human resources, although it is possible to consider other tangible or intangible resources as well. Thus, human resources can be further differentiated in supplier's employees, provider's employees and customers. Relevant characteristics of the employees were identified from our exploratory survey *(Petz et al., 2012)*. Specific characteristics with significant impact on overall productivity are the ability *(comprising qualification and experience)* of the employees as well as their availability and cost rate.

The relationship between human resources and organizational roles is modeled in the domain mapping matrix "Employee/Role DMM", a non-square matrix quantifying the ability of the given person on a scale from zero *(none)* to one *(perfect)*. A role is a person independent organizational unit that combines in a goal-oriented manner a series of abilities in order to run an activity. A role defines a profile of the working unit, thus enabling a flexible and scalable assignment of employees to activities *(see* **Figure 1***)*.

2.2 Service Process Dimension

The process dimension describes the sequence of activities for fulfilling a specified task defined by the mission statement. A process chain is thus composed of specific tasks and their interdependencies.

In contrast to traditional approaches where the activity is specified only by a time span, a service task is specified by an expected work effort quantified in full time equivalents. Because of the uncertainty induced by the customer the effort is estimated by continuous-type random variables with a beta-distribution. Such a distribution is constructed by three estimates: the optimistic, the pessimistic and the most likely value. Furthermore, in order to accurately model the influence of specific customers or stakeholders a minimum working time as well as a reasonable degree of task incompleteness can be assigned to specific activities not visualized here. The activity duration is automatically computed according to the parameterization of the model by the simulation algorithm presented in section 3.

For each task the requirements regarding specific roles, requested suitability as well as quantitative demands are defined. Resources are assigned to the activities according to these requirements. The requirements are specified in the "Activity/Role DMM" as the quantity of the requested resource of a specific kind, thus closing the gap between activities and employees.

The "Process DSM" is a square matrix modeling the service process chain, the tasks and their interdependencies using the IR/FAD convention according to Eppinger and Browning *(2012)*. **Figure 1** depicts the parameterization in a simplified manner. Besides, the possibility considering sequential, parallel and coupled activities enables to model overlapping and iterations by using conditional parameters. Overlapping is depicted in a simplified manner in **Figure 1** on the feed forward path, below the main diagonal. The values in the matrix cells represent the degree of completion of the predecessor task respectively the required input from the upstream task, e.g. task 1 has to be 20% finished in order to start task 2. This is requisite but not sufficient for executing the activity as resource constraints are also considered.

An iteration is modeled by a probability density function above the diagonal. Furthermore, learning is also considered as the decrease rate of the iteration probability but for reasons of simplicity not shown in the figure.

2.3 Service Outcome Dimension

The service outcome dimension represents the overall key performance indicators. Overall duration, cost and capacity utilization are computed and visualized. These overall indicators consider not only resource characteristics like availability but also process characteristics like task interrelations and additional effort due to overlapping or iteration induced rework. These indicators are to be evaluated in concordance with the service objectives from specific service level agreements or by stakeholders in a multidimensional system of weighted objectives. They serve as decision support for the optimization of the service system and delivery.

3. Simulation Algorithm

A Monte-Carlo simulation algorithm was developed and prototypically implemented in MATLAB *(MathWorks)*. The simulation logic is depicted in **Figure 2**. The service process and service structure is modeled in Microsoft Excel and imported automatically into MATLAB. The simulation scenario parameters are also specified and imported in Excel and a new simulation run is triggered.

Non-executed activities are identified and checked for activation. An activity can be activated, when the degree of completion of its predecessor reaches the predefined level as specified in the DSM *(see* **Table 1***)*. At the point of activation of an activity one or more employees are assigned to the activity for execution. The employees are assigned according to their availability and suitability for the specific role. Whilst availability is randomly determined, the mapping of suitability can be done by three different strategies: random, best fit *(in terms of the employee's competence to the required role)* or in a predefined order.

The overall activity effort is determined based on the expected task effort adjusted by the ability of the employee *(qualification and experience)*, additional effort due to task overlapping and employees' interaction quantified by supplementary communication and collaboration efforts. Communication is quantified by an additional temporal effort considering organizational interfaces per employee, summed up and assigned to respective tasks.

Overall activity effort = expected effort of the task + ability effort + overlapping effort+ communication effort – tolerated incompleteness (1)

The activity is executed and the temporal effort of the assigned person is reduced accordingly. Furthermore, iterations are also considered by their probability of occurrence and are processed in the same way. Activities are executed until an abortion criterion is reached *(e.g. the maximum of allowable working hours per day of the assigned employees)* is reached.

The influence of the service customer is considered by a customer specific degree of accepted task incompleteness.

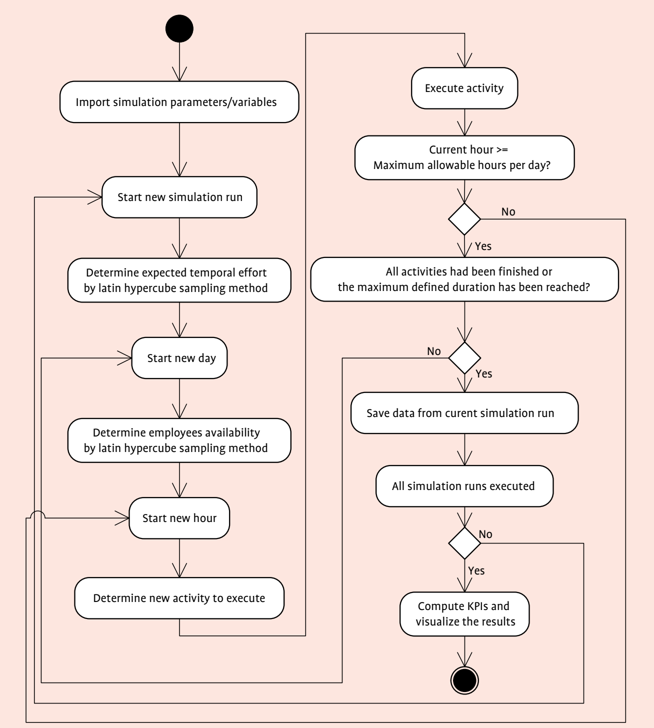


FIGURE 2. *Basic steps of the simulation algorithm*

Therefore, an activity is considered finished when its degree of completion reaches the allowable degree of incompleteness.

When all the activities have been processed, the data of the current simulation run is saved and the KPIs are calculated and visualized. A new simulation run is started and computed in the same way as previously described. After the predefined numbers of simulation runs were processed, overall results are computed and visualized.

4. Case Study

The case study presented in this paper is an excerpt of an engineering service in the chemical industry. It focuses on the development of a piping and instrumentation diagram *(PID)*.

4.1 Study design

The case study presents early activities during the process design phase of a chemical plant development project. In the first step, CAD design parameters and design rules are defined by the project leader as starting point for the chemical process specification. Based on a rough chemical process plan the detailed process layout is drawn using CAD-software. The finalized process layout has to be proofed and commented. Following the amendments for modification the CAD-drawing is revised and finally released.

In this case study we analyze two different organizational designs. In the first setting two process engineers are assigned to work on the tasks, in the second setting the two engineers are assisted by a technical drafter. The case study aims at determining the differences between the two organizational designs in terms of overall productivity.

4.2 Simulation input and independent parameters

Table 1 shows two different parameter settings of the engineering process with different resource allocations. In the square matrix on the left *(process DSM)*, task interrelations are modeled. Entries on the gray diagonal represent the estimates of the expected task effort of a full time equivalent employee with 1.0 ability. For example, considering the first task, one skilled employee has to work at least 4 hours to finish the activity. Most likely he has to work 8 hours, in worst case 16 hours. Entries below the diagonal represent the condition for task activation. In order to activate the second activity, the first activity has to reach a degree of completion of 70%. Entries above the diagonal represent iteration probabilities. The probability that the second task has to be iterated again after the third task is 10%.

The assignment of the employees is given by the intra-domain matrix on the right. Three different roles are considered: employee 1 *(E 1)* as project leader, employee 2 *(E 2)* as process engineer and employee 3 *(E 3)* as technical drafter. In this simplified case there is only one person assigned for each role, thus the employee-role DMM is obsolete. An employee can be accounted for the given task; he is responsible for task fulfillment. A consulted employee has to provide all necessary information to the responsible person.

Activities may start before the end of their predecessor although they lack of needed information. Therefore additional work effort quantified by a linear function of the remaining effort multiplied by the rework effort rate of 0.3 is considered. Learning effects are taken into account by a decrease of the iteration probability of 0.5. Furthermore, the availability of the employee for the case study project is given and limited due to commitments in other projects. The project leader has a most likely availability for this project of only 20% *(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 included by an additional effort of 1 hour per employee and week. Also considered but not depicted here is a reasonable incompleteness of task number three of 20%.

4.3 Simulation results

The service processes were simulated under both organizational conditions. For each condition 10,000 independent runs were computed. The results of the key figures are presented in **Table 2**.

From these results, the first conclusions to the particular features of the specific project settings are derived. A faster processing occurs in the second scenario, due to the involvement of all three employees. The average project duration is reduced by 3 days. In turn, the total effort and costs increased. This is caused especially because of the higher communication effort due to additional interrelations. Furthermore, the process engineer is supported by the drafter, so that his utilization decreases accordingly.

The relative capacity utilization in the first scenario is high with a level of 60% and 85% respectively. The utilization of the project manager even increases in the second scenario, the relative utilization of the technical drafter is only 25%. Thus, the result under the given conditions shows that only 25% of the originally scheduled time is used. This is possibly due to poor planning and allows other allocation of the technical drafter in further projects.

In particular the activities 4-6 in the second scenario exhibit higher expenses as well as higher variations. This is due to task sharing with the drafter. The second scenario has thus an about 10% higher deviation of time, effort and costs.

Summing up the simulation results, the first scenario is robust *(low variance)* regarding duration and costs, while exposing a high risk of capacity unavailability due to high capacity utilization. The second scenario is more flexible from the resource allocation point of view thus exposing high variability in service delivery.

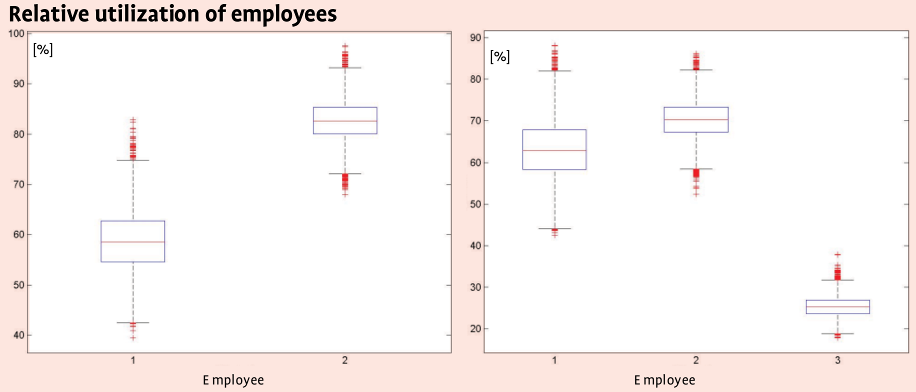
								Setting 1			Setting 2		
Task	**1**	**2**	**3**	**4**	**5**	**6**	**7**	**E1**	**E2**	**E3**	**E1**	**E2**	**E3**
1 Defining CAD design rules	4/8/16							R	C	X	R	C	X
2 Chemical process development	0.7	6/8/12	0.1	0.2				R	C	X	R	C	X
3 Drafting the process chart		0.1	14/20/25	0.5				X	R	X	X	R	X
4 Drawing the process in CAD		0.7	1.0	8/10/12				C	R	X	C	C	R
5 Proof and amend CAD-drawing				1.0	4/8/10			C	R	X	C	R	C
6 Revision of CAD-drawing					1.0	3/5/6		C	R	X	C	C	R
7 Final release						1.0	2/4/5	C	R	X	C	R	C

Legend: R Responsible
C Consulted
X not assigned

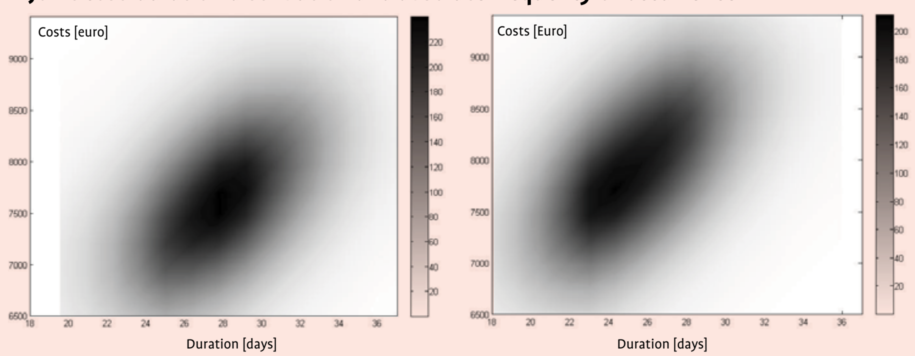
TABLE 1. *DSM and DMM representing two different case study settings*

Setting 1	Setting 2
Without support of technical drafter	**With support of technical drafter**
Average duration: 29 days (SD: 2,5)	Average duration: 26 days (SD: 2,7)
Average effort: 86 hours (SD: 6,0)	Average effort: 94 hours (SD: 6,5)
Average costs: 7,749 Euro (SD: 533)	Average costs: 8,058 Euro (SD: 572)

Relative utilization of employees



Joint cost-duration distribution and absolute frequency of occurrence



Note: SD = Standard Deviation

TABLE 2. *Simulation results of two different service settings*

5. Outlook and future research

In this paper an approach to modeling and simulation of different service systems was presented and advantages demonstrated on the basis of an industrial case study. Further validation studies will be conducted. In particular, sensitivity analyses have to be carried out, in order to determine the robustness of the project to systematic parameter variation *(such as the absence of an employee or a delay in delivery of a supplier)* and the accuracy of the simulated KPIs regarding various project settings *(e.g. inclusion of additional staff, release an employee from other projects)*. Based on the experience in the real service project planning and provision the simulation results will be tested in terms of their realism, examining the applicability of the system in practice in more detail.

Moreover, it is planned to gradually expand the simulation model to incorporate a multicriteria optimization algorithm to enhance service managers' decision support system.

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