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Robust capacity planning for the delivery of Industrial Product-Service Systems

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Abstract

Industrial Product-Service Systems (IPS²) are integrated product and service offerings that deliver superior customer value in industrial applications by mutually determined planning, development, delivery and use of product and service shares. A particular challenge for the provision of IPS² is the planning of resources, e.g. field service engineers (FSE). As a consequence, organizations which offer IPS² or industrial services experience a lack of decision support in determining robust capacity planning strategies in highly dynamic and uncertain environments. In this paper, a simulation-based capacity planning approach is introduced. The focus is on capacity planning of FSE for IPS² delivery in IPS² or service networks. After some general considerations on robust capacity planning for IPS² delivery with the help of scenario simulations, the core elements of the agent-based simulation approach are presented. The most important parameters, control variables and performance indicators are discussed and the procedure of simulation-based scenario planning is outlined.

Keywords: "Industrial product-service systems; robust capacity planning; service delivery; agent-based simulation"

1. Introduction

In order to gain competitive advantage by providing superior customer value, manufacturers in mechanical and plant engineering increasingly recognize the need to provide lifecycle-spanning industrial services to maximize the performance of the physical equipment that is provided to the customer. This necessitates a strong integration of industrial products and services and has led to a new understanding of business relationships which is commonly referred to as Industrial Product-Service Systems (IPS²). IPS² are integrated solutions which provide enhanced customer value through integrated planning, development and operation of products and services [1]. A particular challenge during the operation of IPS² is the management and scheduling of required resource capacity for IPS² delivery. Firstly, the long-term capacity demand needs to be determined during strategic capacity planning. Secondly, during operative delivery planning, delivery processes need to be scheduled and assigned to available resources.

The presented paper focuses on strategic capacity planning and management. This includes the analysis of the currently available resource capacity, most importantly in the form of field service engineers (FSE), and the adjustment of qualitative and quantitative resource capacity based on the current performance of IPS² delivery and future demand situations. A robust planning approach is required because IPS² delivery and resource requirements are subject to various types of uncertainty [2]. For this purpose, an agent-based simulation-model of IPS² delivery is developed. This simulation-model predominantly addresses after sales services such as installation, maintenance and repair activities, which need to be delivered by experienced FSE.

With the help of key performance indicators, which allow quantifying the efficiency and effectiveness of IPS² delivery, different options of capacity management can be evaluated in simulation scenarios with varying parameters, e.g. market
development or technological innovations. Based on these scenarios, the robustness of capacity management policies in situations of internal and external disturbances and fluctuations can be analyzed. The presented approach can be of great value for service organizations and IPS² providers, which are in need for decision support systems for determining resource capacity requirements for robust service delivery in long-term planning situations.

2. Capacity planning for the delivery of Industrial Product-Service Systems

During IPS² operation, the IPS² provider needs to provide the required resources for service delivery at the right quality and quantity at the right time and place. Thus, the basic problem of IPS² delivery planning is similar to production planning and scheduling. However, there are specific challenges, which need to be met during IPS² delivery planning. One characteristic of service delivery is the integration of external factors, e.g. in the form of the machine itself, customer personnel or other customer resources such as cranes, tools or energy supply. Furthermore, service delivery processes are often characterized by high levels of time-criticality. Travel planning, tool and spare part management are also integral parts of IPS² delivery planning. Another important factor is that, unlike physical goods, IPS² delivery processes are perishable, meaning that they cannot be “produced on stock” in order to balance demand peaks. [3,4]

2.1. Capacity planning and resource scheduling

To cope with the above given challenges of IPS² delivery planning, the planning problem can be broken down into sub-problems. Widely acknowledged is the classification according to the length of the planning horizon, which can be found in production management [5], supply chain planning [6] and service delivery planning [7,8]. Hence, in this paper, a differentiation between strategic and operational planning will be made according to the following characterization.

During strategic IPS² delivery planning, the required resource capacity for IPS² delivery is set up with respect to both quantity and quality. Among other, this includes the recruiting and training of field service engineers (FSE). The time horizon of strategic planning is dependent on the adaptability of resource capacity – in the case of FSE, a time horizon of at least one year should be assumed. In this paper, this kind of strategic planning will be referred to as capacity planning.

Operational planning represents the short-term perspective of delivery planning. Here, existing resources are assigned to specific delivery processes. This assignment problem includes matching requirements with qualifications and route planning with multiple distributed resources and individual means of transportation under consideration of time window constraints. In the following, operational planning will be referred to as resource scheduling.

Besides having disparate time horizons, capacity planning and resource scheduling are allocated at different levels of decision-making. Whereas resource scheduling is executed by the dispatcher at the operational level, capacity planning is usually connected to budget decisions or even company policy on a management level. On the operational level, execution support is needed in the form of IT systems, e.g. IPS² Execution Systems [9]. Optimally, resource scheduling, including all related sub-problems, is automatized as far as possible. In contrast, capacity planning cannot be automatized. Instead, decision support systems, which provide relevant information and help to evaluate and compare different options of capacity management, are needed [10].

2.2. Robustness in strategic planning

In strategic planning for IPS² delivery, the development of robust capacity plans is of outmost importance. The reason for this is a combination of certain IPS²-specific characteristics.

Firstly, similar to service delivery, there exist different types of external uncertainties during IPS² delivery. Customer-induced variability is the consequence of variability in the type, time and amount of customer demand in combination with the perishability of delivery processes. The integration of the external factor (customer personnel, machines or other resources) is another cause of uncertainty [11].

Secondly, internal uncertainty within the IPS² network is caused by the collaboration of different delivery partners, the possibility of sudden losses of capacity and higher uncertainties regarding the duration of delivery processes, which usually are less standardized than manufacturing processes.

Thirdly, in IPS² delivery, there often is a high time criticality. This is further increased by IPS²-specific business models (e.g. availability- or result-oriented), which might require a high reactivity of the provider. Hence, due to the transfer of risk to the provider, equipment downtime and bottlenecks in capacity supply can have serious financial consequences. Robustness has several sub-dimensions, which are not always used in a coherent and concise way. Within this publication, the term resilience is understood as the inherent resilience of the capacity plan against disturbances and fluctuations. In order to balance demand peaks. [3,4]
stability of a plan. The more resilient a plan is, the lesser are the effects of external disturbances on the plan.

As opposed to this, the flexibility of a plan describes its inherent ability to adapt to unforeseen developments [12]. Since robustness includes both stability (resilience) and flexibility, a robust plan should contain a stable basic plan and one or several back up plans which need to work together [12].

As explained above, in IPS² delivery, there will always be uncertainty which is caused by the possibility of unexpected increases in demand and sudden losses of capacity [2]. Strategic stability can be achieved with the help of operative flexibility options. Operative flexibility options are created during strategic capacity planning and applied during operative resource scheduling. The idea of operative and strategic flexibility is visualized in Fig. 1. It is similar to the concept of flexibility and adaptability [13].

In case operative flexibility is not enough to ensure a stable capacity plan, strategic flexibility options in the form of backup plans need to be provided. Compared to capacity re-planning, the utilization of backup plans is much faster and more secure. This is because (1) consequences of these backup plans have been evaluated beforehand, (2) prearrangements for their implementation have been made and (3) the backup plans and the conditions under which they are to be implemented have already been approved by the management. Examples for strategic flexibility might be agreements with service partners, sub-contractors or even customers, which become effective if the actual market growth deviates significantly from the anticipated market growth.

2.3. Scenario management and simulation

Scenario management is a structured method of identifying and describing possible future states in order to define alternative backup plans [14]. For defining an optimal capacity management strategy, including one or several strategic flexibility options, the use of systems scenarios is required. Systems scenarios as defined by [14] include both internal (can be influenced by the organization) and external (are to be considered given) factors.

The aim of scenario management is to define one or more sets of external factors, which are most likely to occur, and one or more sets of internal factors, which represent the best reaction strategy in response to the external factors. Following a focused planning approach, decision makers base their planning on one likely reference scenario. As opposed to this, in a future-robust planning strategy, several possible scenarios are taken into consideration when evaluating the risks and potentials of different strategic management options [14].

Simulation modeling is a prevalent tool for supporting quantitative analyses of different scenarios (e.g. [10,15–17]). A simulation model is a simplified representation of reality and serves as an experimental laboratory for evaluation of management decisions before implementing them in the real world (Fig. 2) [18]. It provides decision support because different types of options can be tested within the safe environment of the simulation model. By comparing the system output for different sets of control variables, the most beneficial management options can be identified for each scenario.

Simulation-based scenario-planning is commonly applied to provide decision support in complex and dynamic environments with high levels of uncertainty, where analytical approaches are of limited usability [17].

3. Simulation-based planning approach

3.1. The simulation model

The objective of the simulation-based planning approach is to design an experimental environment, which is a good representation of the real service organization. To be a good representation for providing decision support in defining a strategy for robust capacity planning, the simulation model needs to fulfill the following requirements:

- Provide the same control variables as in the real world
- Include the same types of uncertainties, represented by stochastic variables, as in the real world
- Provide an overall good representation of the dynamics within the service organization

Referring to Fig. 2, the simulation model must accept the same types of input (control variables) as the real world, and provide a system output in response to the input, which is as close to the output of the real system as possible.

Considering these requirements, an agent-based simulation approach has shown to be most suitable to provide decision support for robust capacity planning for IPS² delivery. As opposed to system dynamics and process-centric discrete event modeling, agent-based modeling (ABM) provides possibilities of defining objects and actors (so-called agents), that move within a geographical area, communicate with each other and respond to events based on internal behavioral rules and states [19,20].

The agent-based model for robust capacity planning consists of machine-agents and field service engineer-agents (FSE-agents) which are coordinated with the help of IPS² delivery requests and assignments. Machine-agents and FSE-agents are located in geographical space, representing the physical layout of the service organization. FSE are assigned to delivery processes based on their skills and geographical location, and the urgency and criticality of delivery processes.

The simulation model will be described in detail in the following sections. It has been implemented with AnyLogic University 6.9.0.
3.2. Machine agents

The physical core of the IPS² is the machine, e.g. a machine tool. In the simulation model, each machine is represented by an agent. Its behavior is defined with the help of behavioral rules, which are based on the machine state and several parameters. The machine agent is a generic class within the simulation model which is instantiated by a set of parameters (e.g. breakdown probability, machine lifetime). That way, different machine types with different parameters can be defined.

Due to the sole focus on the delivery of IPS², in the simulation model, the lifecycle starts with the sale of the machine. After the machine has been installed, it enters the working state.

Maintenance processes are either carried out according to a preventive maintenance schedule (if a full service contract has been signed), or condition-based, if a condition monitoring system has been implemented. These are examples for parameters that can be set individually for each machine or for all machines of a certain machine type.

Whenever a machine fails there is the possibility of repairing it remotely, e.g. with telephone support, or of sending an FSE to repair the machine on site. If a regular maintenance process is due after an on-site repair process has been successfully completed, the maintenance process is carried out subsequently to the repair process – provided that the service technician has the required qualifications and equipment. The statechart of the machine is displayed in Fig. 3.

To reduce the simulation model’s complexity, possible delivery processes are initially limited to machine installation, condition-based and periodic preventive maintenance processes, and corrective maintenance processes, i.e. repair processes. However, extensions of the simulation model to include further types of delivery processes, i.e. operator trainings, process optimization or software updates are fully possible.

3.3. Field service engineer agents

The statechart of FSE agents, which is displayed in Fig. 4, consists of several composite states. During usual working hours (e.g. between 8 am and 5 pm on workdays), an FSE might either be available for service or unavailable due to sickness, holiday, or trainings. Within the availability state, the FSE might be idle, he or she might be driving to work or to his or her home location, or the FSE might be at work at a customer’s site.

3.4. Geographical space and agent communication

FSE agents physically move through the geographical area of the service organization. For simplification reasons, in the simulation model, they travel with a constant speed along the direct line between two locations. Agents are placed on the map based on geographic coordinates, which are derived from the street addresses of FSE home locations and customer production sites.

In the simulation model, machine agents and FSE agents communicate either by sending messages or with the help of service missions. Whenever a machine requires some kind of service, a mission is created. The mission contains information regarding the machine, the type of delivery process, the due date of the mission and the FSE, which has been assigned to complete this mission. The assignment of FSE to missions is conducted based on the skill requirements of the delivery process and the skills of the FSE, the locations of FSE and machines and the due date of the mission. For this purpose simple and fast route planning heuristics, such as an insertion heuristic, have been implemented. Of course there are more elaborate and accurate planning algorithms for optimizing the operative scheduling of missions, e.g. the evolutionary meta-heuristic presented in [21], but it is not the aim of the simulation-based strategic planning approach presented in this study to optimize operative planning solutions.

3.5. Data model, parameters, control variables and KPIs

The simulation model is based on a comprehensive data model which is an extension of the data model required for operative resource planning for IPS² delivery [9,21]. This particularly concerns FSE including skills and availability periods, delivery processes including process times and skill requirements, and location information of resources and machines. Unlike operative resource planning, in the simulation-based strategic planning approach missions are
created by discrete events, which occur at regular intervals or according to a probability distribution. Parameters can be adjusted to give a good representation of the real world. These include working time parameters (e.g. working hours, holidays), machine parameters (e.g. full service contract rate, machine lifetime, failure rate), and technicians’ learning effects.

Versatile control variables represent strategic capacity management options and can be used to control the system output. These include the following:

- Hiring or lay-off of FSE
- Qualification of FSE
- Relocation of FSE
- Product modifications, e.g. increasing maintainability or invention of condition-monitoring sensors
- Preventive maintenance periods
- Remote service / visual online support tools, which increase the remote service completion rate and thereby help to avoid field service missions
- Delivery process priorities and time windows

To evaluate the system output, key performance indicators (KPI) are required. Relevant KPIs that are evaluated to assess the performance of the IPS² provider and thus the effectiveness of the strategic capacity planning options include mean down time (MDT), mean time to problem solution (MTPS), mean time between failures (MTBF), on time delivery (OTD), workforce operating/driving/idle time and the amount of corrective and preventive maintenance activities [22]. In Fig. 5 KPI charts from the capacity management cockpit of the simulation are shown. Additionally, an Excel-export of all relevant KPIs has been implemented.

3.6. Procedure of simulation-based scenario planning

Simulation-based scenario planning is an iterative approach. It is aimed at finding multiple sets of control variables, which are most suitable to achieve high-levels of congruence between target and performance KPIs. Target KPIs and one or several sets of scenario parameters (one set for each scenario) constitute the input to the simulation study.

In an iterative approach, strategic capacity management options, which have been introduced in the previous section, are implemented based on external parameters and target-performance comparisons of previous simulation runs. Due to stochastic simulation variables, repeated simulation runs with identical parameters and control variables are to be conducted in order to be able to evaluate performance KPIs on a statistical basis. A set of capacity management options, for example a combination of hiring and training of FSE, is suitable for a specific scenario definition when performance KPIs are within a predefined target corridor. The iterative approach of simulation-based scenario planning is visualized in Fig. 6. [17]

4. Discussion and Outlook

In this paper, a simulation-based approach for robust capacity planning for IPS² delivery has been presented. The purpose of the planning tool is to provide decision support in complex strategic planning situations, which are characterized by high levels of uncertainty. With the help of the presented tool, service managers are able to test and evaluate the effect of costly capacity management options before actually implementing them in the service organization. Several alternative scenarios can be simulated and the chances and risks
of the management options can be assessed, taking into consideration the probability of different developments of external scenario parameters. The stability of a plan can be assessed by simulating a number of external scenarios, in which the internal parameters of the capacity management strategy remain stable. As the second dimension of robustness, the flexibility of a capacity plan is assessed by considering the amount of internal change necessary to cope with large-scale external developments.

This kind of decision support cannot be provided by analytical approaches. Firstly, a multitude of simplified assumptions would have to be made to limit the complexity of the planning problem. Secondly, uncertainties and dynamics in the form of stochastic probability distributions and state-dependent behavior of agents cannot be considered in analytical models. Thirdly, analytical approaches do not provide a test environment for the evaluation of different capacity management options.

A limitation of the presented approach is that the validity of the simulation results is strongly connected to the quality of the simulation model and the available data. There might be important factors of influence in the real service organization, which cannot be included in the model. Moreover, simplifications have to be made and some assumptions about agent behavior might not be generally applicable in reality. Another important limitation is that the presented approach is not suited to define appropriate capacity management strategies – its strength lies in revealing the consequences of different options. Thus, the outcome of the planning task is strongly determined by the creativity, the insights and understanding of the service manager or consultant who is working with the decision support tool.

In order to facilitate the industrial applicability of the decision support tool, efforts should be made towards the integration of the presented simulation tool with existing tools that support the operational scheduling of resources for service or IPS² delivery. Because most of the data is the same for operational resource scheduling and strategic capacity planning, the integration of both approaches into one holistic system seems to be the logical consequence.

Up to now, the decision support tool has been evaluated with the help of different fictional test scenarios and an exemplary data set within a real industrial setting. However, comprehensive quantitative tests have not been conducted, yet. This will be the focus of future studies.

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