

Christo Apostolov

**Integrative Methodology for
Model-Based Engineering of
Smart Product-Service Systems**

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Christo Apostolov

Abstract

This Ph.D. thesis on the topic of smart product-service systems (PSS) engineering peruses the goal of integrating the processes of service and digital infrastructure development and connecting the development processes of related products and organizational units, thereby providing an overall framework for smart PSS engineering endeavors.

A methodology elaborated following the *CASE Research Cycle* achieves this goal. The proposed methodology is meant for application in PSS development projects, covering the stages of business model analysis and specification, conceptual PSS design, detailed service and digital infrastructure design, and design validation and testing. The methodology comprises two levels on which the PSS development endeavor is considered.

A macro-level is concerned with the overall development process, the PSS typology, and enterprise-wide integrated IT landscape supporting the entire lifecycle of the system under development. This level aims to establish an overall understanding of the development endeavor among stakeholders, set the conceptual model for PSS consideration, and guide the overall development process. On the macro level, the methodology comprises a process model, a typological PSS model, and an IT architecture concept. These represent extensions, respectively adoptions, of the three components of the *VPE-SDM* methodology for cybertronic system development.

A micro-level concerned with the design of the services and digital support infrastructure of the PSS and the provision of connection paths to associated product development processes provides a process definition for system analysis and design synthesis, a concept based on an ontology, views, viewpoints and a meta-model for system representation in the Systems Modeling Language (OMG SysML), and prototypical integrations for modeling support in professional tools. In addition, design verification and validation are supported by the formality and simulative executability of SysML models and the possibility of implementing digital twins in early-deployed instances of the PSS operating system.

The applicability and suitability of the proposed methodology are demonstrated with the help of a fictive case study of an *Autonomous excavation site PSS*. The study includes the PSS modeling and the exemplary implementation of service processes based on digital twins of the system and its process-relevant elements in an industrial IoT solution functioning as the PSS operating system.

Kurzfassung

Die vorliegende Dissertation zum Thema Smart Product-Service Systems (PSS) Engineering verfolgt das Ziel, die Prozesse der Entwicklung von Dienstleistungen und digitalen Infrastrukturen zu integrieren, und die Entwicklungsprozesse dazugehöriger Produkte und Organisationseinheiten damit zu verbinden, um so einen Gesamtrahmen für intelligente PSS-Engineering-Bestrebungen zu schaffen.

Dieses Ziel wird durch eine Methodik erreicht, die nach dem *CASE-Forschungszyklus* entwickelt wurde. Die vorgeschlagene Methodik ist für die Anwendung in PSS-Entwicklungsprojekten gedacht und deckt die Phasen der Geschäftsmodellanalyse und -spezifikation, des konzeptionellen PSS-Entwurfs, des detaillierten Entwurfs von Diensten und digitaler Infrastruktur einschließlich Entwurfsvalidierung und -test ab. Die Methodik berücksichtigt zwei Konkretisierungsebenen bei der PSS-Entwicklung.

Eine Makroebene befasst sich mit dem gesamten Entwicklungsprozess, der PSS-Typologie und der unternehmensweiten, lebenszyklusübergreifenden, integrierten IT-Landschaft. Ziel dieser Ebene ist es, bei den Beteiligten ein Gesamtverständnis für das Entwicklungsvorhaben zu schaffen, das konzeptionelle Modell für die PSS-Betrachtung festzulegen und den gesamten Entwicklungsprozess zu steuern. Auf der Makroebene umfasst die Methodik ein Prozessmodell, ein typologisches PSS-Modell und ein IT-Architekturkonzept, die eine Erweiterung bzw. Übernahme der drei Komponenten der *VPE-SDM-Methodik* für die Entwicklung cybertronischer Systeme darstellen.

Eine Mikroebene, die sich mit der Gestaltung der Dienste und der digitalen Unterstützungsinfrastruktur des PSS und der Bereitstellung von Verbindungspfaden zu zugehörigen Produktentwicklungsprozessen befasst, bietet ein Prozessmodell für die Systemanalyse und die Entwurfssynthese, ein auf einer Ontologie basierendes Konzept mit Sichten und Gesichtspunkten, und ein Meta-Modell für die Systemmodellierung in der Systems Modeling Language (OMG SysML), sowie prototypische Integrationen für die Modellierungsunterstützung in ausgewählten kommerziellen Tools. Die Entwurfsverifikation und -validierung wird durch die Formalität und damit simulative Ausführbarkeit von SysML-Modellen und die mögliche, frühzeitige Implementierung von digitalen Zwillingen in früh aufgestellten Instanzen des PSS-Betriebssystems unterstützt.

Die Anwendbarkeit und Eignung der vorgeschlagenen Methodologie wird mit Hilfe einer Fallstudie des fiktiven Beispiels einer autonomen Baustellen-PSS demonstriert. Das Beispiel umfasst die PSS-Modellierung und die beispielhafte Implementierung von Service-Prozessen auf der Basis von digitalen Zwillingen des Systems und seiner prozessrelevanten Elemente in einer industriellen IoT-Lösung, die als PSS-Betriebssystem fungiert.

Резюме

Тази докторска дисертация на тема "Разработка на интелигентни продукт-сървис системи (PSS)" има за цел да интегрира процесите на разработване на услуги и цифрова инфраструктура и да свърже процесите на разработване на принадлежащи към системата продукти и организационни единици, като по този начин да осигури цялостна рамка за разработване в областта на интелигентните PSS.

Тази цел се постига с методология, разработена в съответствие с изследователския цикъл *CASE*. Предложената методология е предназначена за прилагане в проекти за разработване на PSS, като обхваща етапите на анализ и спецификация на бизнес модела, концептуално проектиране на PSS, детайлно проектиране на услуги и цифрова инфраструктура, включително валидиране и тестване на проекта. Методологията разглежда две нива на конкретизация в начинанието за разработване на PSS.

Макроравнището е свързано с цялостния процес на разработване, типологията на PSS и интегрираната информационна инфраструктура на цялото предприятие, поддържащ целия жизнен цикъл на разработваната система. Целта на това ниво е да се установи цялостното разбиране на начинанието за разработване сред заинтересованите страни, да се определи концептуалният модел за разглеждане на PSS и да се направлява цялостният процес на разработване. На макроравнище методологията се състои от модел на процеса, типологичен модел на PSS и концепция за информационната инфраструктура, които представляват разширения, респективно приемане на трите компонента на методологията *VPE-SDM* за разработване на кибертронични системи.

Микроравнището, свързано с проектирането на услугите и инфраструктурата за цифрова поддръжка на PSS и осигуряването на възможност за връзка със свързаните процеси за разработване на продукти, предоставя дефиниция на процеса за анализ на системата и синтез на дизайна, концепция, основана на онтология, изгледи и гледни точки и метамодел за отразяване на системата в езика за моделиране на системи *OMG SysML*, както и прототипни реализации за поддръжка на моделирането с чрез етаблирани софтуерни инструменти. Проверката и валидирането на дизайна се подпомагат от формалността и по този начин симулативната изпълнимост на *SysML* моделите и възможността за ранно реализиране на цифрови близнаци в ранно внедрените инсталации на PSS операционната система.

Приложимостта и пригодността на предложената методология е демонстрирана с помощта на фиктивен пример за автономна PSS система за строителни изкопи. Анализът включва моделиране на PSS и примерна реализация на процеси на обслужване въз основа на дигитални близнаци на системата и нейните елементи, свързани с процесите, в индустриално IoT решение, функциониращо като операционна система на PSS.

Resumen

Esta tesis doctoral sobre el tema de ingeniería de sistemas inteligentes de producto-servicio (PSS) persigue el objetivo de integrar los procesos de desarrollo de servicios e infraestructuras digitales y conectar los procesos de desarrollo de productos y unidades organizativas asociadas, en el esfuerzo de proporcionar un marco general a la ingeniería inteligente de PSS.

Una metodología desarrollada siguiendo el ciclo de investigación *CASE* logra este objetivo. La metodología propuesta está destinada para su aplicación en proyectos de desarrollo de PSS, abarcando desde las etapas de análisis y especificación del modelo de negocio, diseño conceptual del PSS, diseño detallado del servicio y de la infraestructura digital, hasta la validación y prueba del diseño. La metodología considera dos niveles de concreción en el esfuerzo de desarrollo del PSS: un nivel macro y un nivel micro.

El nivel macro se ocupa del proceso de desarrollo general, la tipología del PSS y el marco informático que se integra en toda la empresa durante el ciclo de vida completo del sistema en desarrollo. El objetivo de este nivel es establecer un conocimiento general del plan de desarrollo entre las partes implicadas, establecer el modelo conceptual para la consideración del PSS y guiar el proceso de desarrollo general. En el nivel macro la metodología se compone de un modelo de proceso, un modelo tipológico de PSS y un concepto de arquitectura informática que representan extensiones, respectivamente, de los tres componentes de la metodología *VPE-SDM* para el desarrollo de sistemas cibertrónicos.

El nivel micro, que se ocupa del diseño de los servicios y la infraestructura de soporte digital del PSS y la provisión de rutas de conexión de los procesos de desarrollo de los productos asociados, proporciona un modelo del proceso para el análisis del sistema y la síntesis del diseño, un concepto basado en una ontología, diferentes puntos de vista y un metamodelo para la representación del sistema en el Lenguaje de Modelado de Sistemas (OMG SysML), así como integraciones prototípicas para el apoyo del modelado de herramientas comerciales seleccionadas. La verificación y validación del diseño se apoyan en la formalidad y, por lo tanto, en la viabilidad de ejecución de la simulación de los modelos SysML y en la posible implementación de gemelos digitales en instancias tempranas apoyadas por el sistema operativo PSS.

La aplicabilidad e idoneidad de la metodología propuesta se demuestra con la ayuda de un estudio de un caso ficticio de una excavación autónoma en PSS. El estudio

incluye el modelado del PSS y la implementación ejemplar de procesos de servicio basados en gemelos digitales del sistema y sus elementos relevantes para el proceso en una aplicación industrial de IoT, que funciona como sistema operativo del PSS.

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