INTERNATIONAL DESIGN CONFERENCE - DESIGN 2008
Dubrovnik - Croatia, May 19 - 22, 2008.

DESIGN 2008

CONCEPTUAL DESIGN OF INDUSTRIAL PRODUCT SERVICE SYSTEMS (IPS²) BASED ON THE EXTENDED HETEROGENEOUS MODELLING APPROACH

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Keywords: heterogeneous modelling, IPS², early phase

1. Introduction

According to [Tan 06], selling combinations of physical components (products) as well as offering integrated intangibles (services) are just two different modes in which a company delivers value to their customers. Combining the value generation of both modes therefore is a self-evident compromise. Against this background, integrated *Industrial Product-Service Systems (IPS²)* are proposed as a solution to increase value generation. By definition, IPS² are characterized by an integrated and mutually determined process of planning, developing, delivering and using of manufacturing systems and industrial services containing immanent software components. As IPS² focuses on integrating high-investment industrial goods and industrial services it can be considered as a subset of the research field of 'PSS Engineering'.
IPS² thereby serves as a problem solution tailor-made to fit individual customers' needs along the entire life cycle. This is mainly generated through the possibility of partially substitutable IPS²'s artefacts. Compared to pure product offers, like the mere selling of a machine, Industrial Product-Service Systems are characterized by the possibility of exchanging product components with service artefacts and vice versa in order to fulfil required functions during the delivery and use of the IPS². Hence, considering interdependencies between products and services in an early phase of development is not only crucial for the initial determination of product and service components, but also for the definition of their potential for partial substitution.
In the context of IPS² the term 'early phase' is used synonymously to the understanding of this term established in product engineering [Pahl 07]. Therefore an assessable concept constitutes the result of the early phase of development. Following the common understanding of the term 'concept', an IPS²-concept contains any elements and essential relations in between these elements to represent its fundamental properties on a higher level of abstraction. Thus, an IPS²-concept poses the initial basis to assess technical as well as economic systems states and to simulate its systems behaviour.

2. Objectives

As an IPS-concept marks the initial transformation of a development idea into an assessable model, a consistent understanding of the term 'IPS² concept model' is required and a methodical modelling approach needs to be proposed. Existing PSS modelling approaches are mainly holistic concerning modelling PSS-concepts and do not take special characteristics of integrating industrial goods and industrial services into account. Hence, no applicable approaches to develop and to represent IPS² concept models in the early phase of IPS²-development currently exist.
This paper aims at a systematic extension of the heterogeneous modelling approach in mechatronics to model IPS²-concepts. Therefore, chapter 3 gives an introduction to interdisciplinary modelling

approaches and focuses on the basics of heterogeneous modelling of mechatronic systems. Chapter 4 contains a deduction of the theoretical framework which serves as the basis to extend heterogeneous modelling to IPS² concept modelling. Chapter 5 serves to propose the basic idea of heterogeneous IPS² concept modelling. This paper concludes in Chapter 6.

3. Interdisciplinary modelling approaches

Following the general understanding of the term ‘model’ [Jansen 05], a model in an IPS² context denotes a consciously constructed aim-oriented representation of an original. A model serves the purpose of enabling both analysing and synthesising steps. Depending on the focus of the respective development disciplines, manifold modelling approaches have emerged. Despite their differences, these approaches often reveal similarities which are ascribable to systems engineering theory. However, the characteristics of a modelling approach are offering the possibility to either specifically describe a narrowly defined domain of application or to comprehensively support modelling across domains.

3.1 Modelling of PSS

Service Engineering (SE), as proposed by [Sako 06], aims to model services and physical product artefacts by offering elements called “content” and “channel” as means of realizing services. Service contents are material, energy and/or information whereas the service channel consumes these elements during service delivery. Following this understanding a physical product either consists in a service content or in a service channel and can be modelled using conventional product design approaches. Service engineering focuses on describing the process of changing conditions of the service recipient on a low level of abstraction [Sako 06]. Moreover, no integration of products and services on a conceptual level of development takes place. As a consequence, the mutual determination of products and services in the early phase of development is neglected.

Following the CPM/PDD approach, originally designed to develop and design physical products, [Weber 04] proposes to extend this approach to model PSS. Building on classical design theories, modelling PSS is based on distinguishing between “characteristics” and “properties”. According to [Weber 04] the main problem in modelling PSS consists in the distinction between product and service. The extension of the CPM/PDD approach for the first time attempts to dissolve the separation between products and services and to replace it by an alternative perspective.

3.2 Heterogeneous modelling in mechtronics

As aforementioned, physical products in the context of IPS² are primarily related to high-investment industrial goods, which to a great extend contain mechatronic components. Based on a product oriented perspective the ‘heterogeneous modelling approach in mechatronics’, proposed by [Jansen 05], is suitable to serve as a basis to integrate conceptual modelling of industrial product and service artefacts.

This modelling approach has been developed to engineer mechatronic systems with the primary aim of enabling spatial and functional domain allocation in early phases of development, which can be considered as partial substitution on a mere technical level. The approach aims at modelling elements of a mechatronic system, which refer to different levels of abstraction, formalization, and detailing within one integrated heterogeneous model. To do so, constructs for modelling, such as *system elements* (functions, working principles, components), *system relations* (directed, undirected, functional, organizational) and *context relations* (requirements, engineering resources, etc.) are embedded in an object oriented modelling notation.

Figure 1 illustrates main characteristics of this approach by displaying a heterogeneous model of a multi-body actuator. This model consists of spatially allocated functions, medium abstracted working principles (see [Pahl 07]) and a fully designed component. Therefore, a semi-formal graphical notation is used. Since this approach focuses on creating models which are used to simulate functional behaviour of mechatronic systems in the conceptual development phase, it gains in importance to support modelling by a CAx tool.

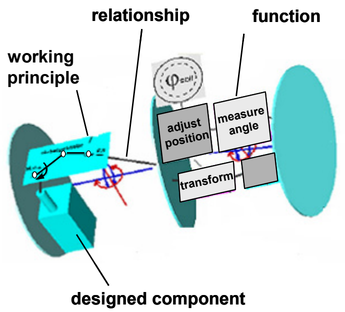

Figure 1. Heterogeneous modelling in mechatronics

4. Theoretical framework for IPS² concept modelling

Extending the heterogeneous modelling approach of mechatronics requires the definition of a theoretical framework to provide the basis for IPS² concept modelling. Within this framework, aspects like partial substitution of product and service artefacts, putting product artefacts on a level with mechatronic components, and defining a coherent modelling basis for products and services have to be given special consideration.

4.1 Definition of the formalized IPS² modelling space

The formalized IPS² modelling space is based on the determination of the three fundamental modelling axes, "detailing", "abstraction", and "formalization" [Welp 08]. The combination of these axes denotes a formalized product modelling space which serves as the basis for heterogeneous modelling of mechatronic systems. Furthermore, this modelling space supports the connectivity of inherently separated modelling layers to enable the introduction of partial models at any point of the formalized modelling space. As a result of our current research we propose to apply the modelling perspective adopted in product engineering to models in service engineering. To enable the integration of both engineering disciplines the meaning of abstraction regarding immaterial and intangible services in general needs to be discussed (see Chapter 5). By merging product and service modelling spaces, an integrated third space, the formalized IPS² modelling space, is formed as shown in Figure 2.

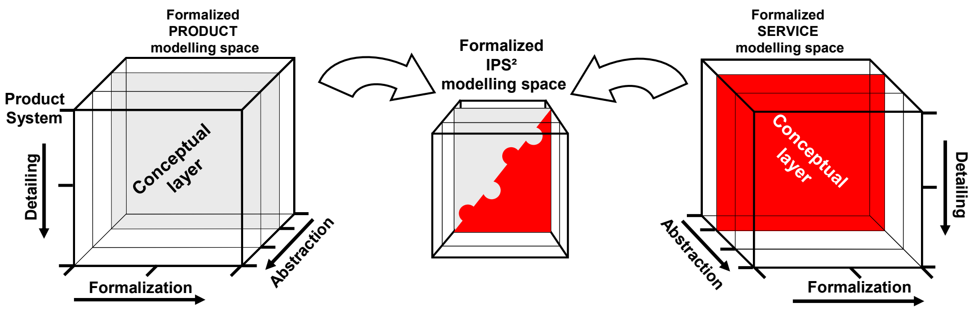

Figure 2. Integration of formalized modelling spaces

The integration of heterogeneous product and service modelling to heterogeneous IPS² modelling offers the opportunity to constitute a generic development path through the IPS² modelling space in order to determine IPS² concept models (see Figure 3).

This path or the early IPS² development phase respectively, starts in the upper left corner (1) by receiving customer requirements. At this stage the entire problem is modelled textually and therefore in an informal way. In the course of creating IPS² concept models the second point in the modelling space (2) has to be reached by detailing and formalizing those requirements. Suppliers use the processed and semi-formalized requirements as system specifications. According to product engineering methodologies those specifications are needed to derive IPS²-functions (3) which initially describe problem solutions in an abstract, yet more formal and detailed way. In connection with an iterative multistage development process, functions will be concretized to integrated working principles, designed components or service processes (4 a-b-c) containing all associated relations. According to the heterogeneous modelling approach, modelling elements can differ regarding their level of abstraction, detailing and formalization. Finally, the conceptual components (4 a-b-c) need to be integrated into an assessable IPS² concept model (4).

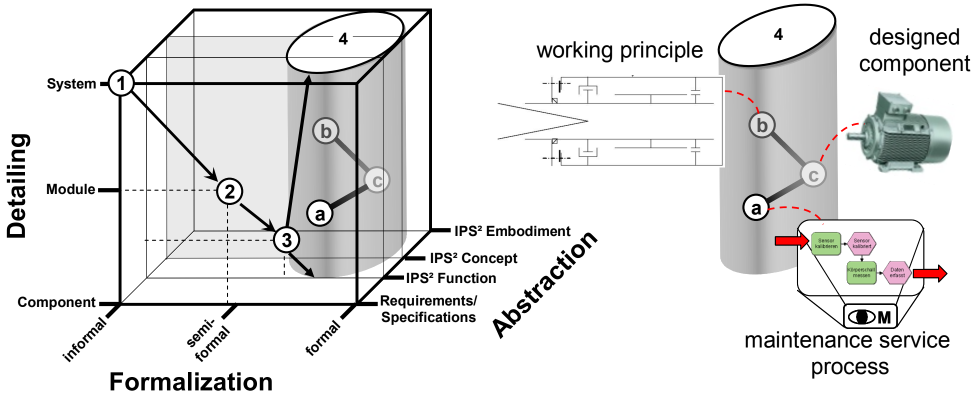

Figure 3. Development path in IPS² modelling space

4.2 Introducing a novel perception of products and services

Service development as well as research has repeatedly stated the existence of unique, inherent service characteristics, which distinguish services from products. These seemingly unique characteristics, however, have to be critically discussed. According to [Tan 06], every product involves services such as sales, delivery and support. Moreover, [Tan 06] also points out that every service involves physical product artefacts in order to generate benefit. Against this background it is difficult to provide a clear distinction between 'service' and 'product'. The second basic module of the theoretical framework therefore addresses the dissolution of boundaries between both. To do so, product and service definitions are contrasted.

'Products' are generally defined as artefacts that supply the consumer with benefits. The production of tangible objects and the respective consumption of these objects usually take place at different locations and at different points in time. Contrary to the understanding prevalent in PSS literature, an industrial product in IPS² context consists of more than mere physical elements. It has to be regarded as a multidisciplinary system, which in its highest degree of specification equals a mechatronic system. According to [Harashima 96], mechtronics is defined as the synergetic integration of mechanical engineering with electronic and intelligent computer control in the design and manufacturing of industrial products and processes.

Emphasizing the service perspective, 'services' are defined as providers' activities aimed at changing recipients' existing states to reach new, desired states [Sako 06]. Furthermore, [Mont 04] defines service as a mainly immaterial, intangible, and perishable activity or process which is produced and consumed simultaneously (uno-actu principle) and cannot be stored. Delivering a service always requires the integration of an external factor (customer). Regarding the special consideration of industrial services in an IPS² context, the general service definition has to be supplemented by the aspects "degree of automation" and "spatial separation of delivery and use". Integrating these aspects increasingly dissolves boundaries between products and services, as the following example illustrates.

Based on the given function of 'adjusting machine behaviour to changing conditions' following customized solutions are possible: i) *Manual service:* Machine and service personnel are not spatially separated. The service personnel follow handbook instructions when reacting to changes in machine behaviour. ii) *Teleservice=semi-automated:* The machine is monitored externally. Manipulations of machine behaviour are carried out by service personnel via IT support located in a control room, which is spatially separated from the machine itself. iii) A*utomated service* = *mechatronic system*: The machine status is monitored by sensors and evaluated via an internal computer control device. Reactions to changes in conditions are carried out by the machine itself by means of mechatronic devices, mostly actuators.

A general reorientation of the perception of products and services is necessary to represent the partial substitution of products and services, respectively the changes depicted in the example, in a model. Viewing products and services on an abstract level, it becomes obvious that in order to fulfil product or service based functions, two types of artefacts are needed in general. As illustrated by the example, *resources*, for instance human resources, sensors, actuators, etc. have to be combined to constitute a physical structure. Furthermore, *actions*, for example maintenance processes, an algorithm for processing a sensor signal etc., need to be determined in order to reach a desired state.

To model the functional behaviour of a system over time, corresponding to a sequence of state changes, actions have to be applied to resources. Only the combination of both artefacts can constitute the desired problem solution and the functional behaviour of the system. The introduction of this new paradigm renders the separation of product and service modelling irrelevant. By defining *IPS²-objects* (resources) and *IPS²-processes* (actions) modelling product and service artefacts can be integrated on one generic level.

5. Extended heterogeneous IPS² concept modelling

Put concisely: In accordance with the generically formulated development path presented in Figure 3, there is a necessity for the transformation of abstract, informal and functionally described customer requirements into an integrated heterogeneous IPS² concept model, which may serve as a basis for the simulation of IPS² systems behaviour. Without delving too deeply into details of the appropriate modelling methodology, it can be said that an extension of heterogeneous IPS² concept modelling requires the consideration of additional super-ordinate aspects such as iterative approaches and a high degree of flexibility in the process of development. The application of the object-oriented paradigm according to [Rumbaugh 90] offers a suitable basis for an efficient IT-based implementation of the extended heterogeneous IPS² concept modelling approach.

5.1 Definition of modelling planes

Building on the theoretical framework, the IPS² concept model is conceptualized as an extension of the heterogeneous modelling approach in mechatronics. It is generated by defining and merging four modelling planes which are called IPS²-function-, IPS²-object-, IPS²-process-, and IPS² systems behaviour-plane (see Figure 4).

The IPS² concept model is structured content-wise into the four aforementioned modelling planes in accordance with the generic development path within the formalized IPS² modelling space. The partial and variously combinable development activities within this frame are based on dominant axes of modelling and may be described as a combination of formalisation, increase of detail and decline in the degree of abstraction. As an extension of the basic heterogeneous modelling approach each modelling plane contains system elements, system relations and context elements. In addition to the plane-specific definition of *elements* (IPS²-function, IPS²-objects, IPS²-process steps, etc.) and types of *relations* (FxF-/ OxO-/ and PxP-relation) and their respective *interfaces*, modelling planes are connected via specific *associative relations* (FxO-/ FxP-/ and OxP-association) in order to link model content. Their functionality reaches from constituting a pointer between IPS²-functions and IPS²-objects, or IPS²-processes respectively, to constituting a point of integration for *operators* and *operands* at the IPS² systems behaviour plane. Moreover, the modelling context, which for instance contains restrictions, domain specifications, or information about related resources, is integrated into the IPS^2 concept model through separate elements. The combination of all planes constitutes the heterogeneous IPS^2 concept model and can be described by an object-oriented class structure.

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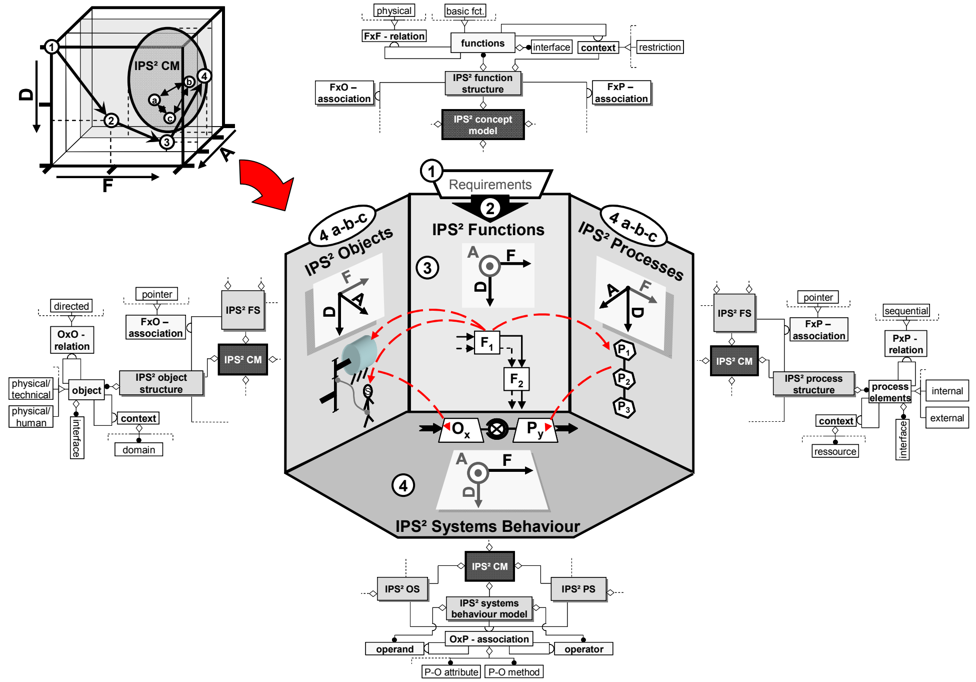

Figure 4. Structure of the extended heterogeneous IPS^2 concept modelling approach

5.2 S^2-functions, IPS^2-objects and IPS^2-processes

Accordingly, modelling IPS^2-functions, as a development activity emphasising "formalisation and detailing", is carried out on the IPS^2 function plane (see Figure4). In the context of extending heterogeneous IPS^2 concept modelling, an *IPS^2-function* equals the uncommitted, abstract representation of intended changes within the IPS^2. These changes are based on the outcome of energy-, material- and information-transactions. The chronological interconnection of states to the functional behaviour of an IPS^2 is only implicitly considered in the structural connection of IPS^2-functions through relations.

Starting from the change in paradigm regarding the understanding of products and services, the part of modelling which emphasises "detailing and abstraction" is allocated on the IPS^2 object plane as well as on the IPS^2 process plane. Within a heterogeneous IPS^2 concept model, aspired changes of states are partially defined by forming and concretizing *IPS^2 object-process pairs*. The connection of these pairs, concerning aspects of content and time, constitutes the explicit basis for modelling the functional behaviour of an IPS^2. The *IPS^2-object* hereby serves as a physical, material point of reference. It is formed by unevenly concretizing mechanical, electronic, human or IT elements. Complementary to this, an *IPS^2-process* marks a structural connection of an initial and a final state, following processing instructions. Accounting for the axes of abstraction in modelling, IPS^2-processes take place along the lines of the heterogeneous modelling of process oriented service attributes. At the most abstract level, an IPS^2-process is determined by defining elements which are part of this process and their undirected linkage. Contrary to the physically oriented concretization of IPS^2-objects, the decline of the degree of abstraction of IPS²-processes is mirrored by the design of the time dependant process parameters. Consequently, a concretized IPS²-process contains timing elements to determine the sequence of processing steps and transitions, which form logical links between these steps.

5.3 IPS² systems behaviour

By applying an IPS²-process to a physical or intangible object, the systems behaviour of an IPS² object-process pair is modelled. The degree of abstraction of IPS² object-process pairs during their deduction from IPS²-functions can vary considerably. As a consequence, the heterogeneity of this modelling approach becomes especially apparent on these two modelling levels.

The behaviour oriented integration of IPS²-objects and IPS²-processes takes place at the IPS² systems behaviour plane. The relevant modelling task consists in formalising operands and operators (see Figure 4). Integrating IPS²-object and IPS²-process plane requires a consistent, universally valid, reference value to generate a model suited for simulation in the early phase of IPS²-development. Based on the approach of 'acausal modelling' [Fritzson 04], the interdisciplinary reference value „power", consisting of "effort-variables" (moment, voltage, pressure difference, etc.) and "flow-variables" (angular velocity, current, volume flow rate, etc.), has to be extended by the necessary modelling constructs of non-physical artefacts in the context of IPS². This IPS² systems behaviour model constitutes the basis for analyzing different IPS² concept models. Evaluating technical as well as economic values leads to identify that concept model which best meets customer requirements. Models' attributes and methods therefore need to be instantiated. Any subsequent simulation necessitates the development of suitable solvers to determine the results of physical as well as process behaviour.

6. Conclusion and outlook

To the challenges companies are faced with today, IPS² could constitute a solution. This paper shows that modelling IPS² concepts in the early phase of development is crucial, especially to consider the partial substitution of product and service artefacts. Based on the determination of the theoretical framework an extension of the heterogeneous modelling approach in mechatronics and the IPS² concept model itself are proposed. As a means of integrating products and services, four different modelling planes have been defined to model IPS²-functions, IPS²-objects and IPS²-processes as well as the IPS² systems behaviour. It is of special interest for further research to implement the approach into a computer aided tool. By applying such a tool to companies' tasks, supplementary insight into potentials and difficulties of this approach could be gained.

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