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Conceptual Development of Industrial Product-Service Systems

A model-based Approach

The increasing competitiveness of today's globalised economies and changing customer requirements prompt manufacturers to provide integrated product and service solutions, referred to as Industrial Product-Service Systems (IPS^2). An IPS^2 constitutes a customised solution, whereas providing performance is set above the purchase of a mere technical product. It can comprise any combination of product and service shares. Once such an offer is planned, the IPS^2 concept development phase generates principle solutions that meet customer-specific requirements. This article presents a model-based methodology to support an IPS^2 designer during the process of generating IPS^2 concepts in the early phase of IPS^2 development. This methodical framework and the modelling approach for conceptual IPS^2 development has been implemented as a computer-aided tool and has been evaluated by solving a typical IPS^2 issue.

1 Introduction

The combination of globalisation effects and technological advances has led to long-term, cooperative customer-supplier relationships and to a decline in the supplier's differentiation solely based on technical products. Today, industrial services have evolved from being peripheral add-ons for technology to become a complementary part of an integral solution.

As the importance of long-term customer-supplier relationships, especially concerning the investment goods industry is growing, the sale of pure technical products has been replaced by new business models. However, the implementation of these business models requires the integration of technical products and industrial services to form product service bundles (Oliva and Kallenberg 2003). In academia these types of solution are called 'Industrial Product-Service Systems' (IPS^2).

To meet customer requirements and to properly develop solution elements as well as relations between them, it is important to consider interdependencies between products and services at an early phase of development (Welp et al. 2008a). There are currently no suitable integrated, model-based approaches available that support IPS^2 designers generating IPS^2 concepts systematically. In order to satisfy this demand, a methodology for the development of IPS^2 concepts is proposed in this article. It is based on a novel modelling approach, so called 'heterogeneous IPS^2 concept modelling'.

To establish a common comprehension of the system to be developed, basics of Industrial Product-Service Systems are addressed in this contribution first. After that, basic aspects of the heterogeneous IPS^2 concept modelling approach and of the design methodology for conceptual IPS^2 development are explained. Furthermore, the implementation of the proposed approach as a computer-aided tool is presented. The conceptual IPS^2 development methodology is evaluated using an IPS^2 specific issue in micro manufacturing industry. The article concludes with a summary and an outlook.

2 Basic Understanding of IPS^2

From a supplier's point of view an Industrial Product-Service System (IPS^2) is a long-term individual problem solution solving business-to-business market issues. During its long-term delivery and use an IPS^2 allows dynamic adaptation to changing restrictions or influencing factors. This specific feature of an IPS^2 is to be considered as 'changeability'.

An IPS^2 meets individual customer requirements by integrating multidisciplinary, technical product components and industrial services. Thus, mechatronic subsystems are immanent constituents of an IPS^2 (Welp and Sadek 2008). They don't only form the technical product needed for manufacturing processes, but are also the basis for automating industrial services.

The aspired change from selling merely technical products or industrial services to a performance-based sale of IPS^2 aims at increasing customer's and supplier's benefits alike. This leads to changing business models as well as to novel customer-supplier relationships. To coordinate business relationships, business contracts are used. Concerning IPS^2, contracts that coordinate a long-term cooperation between contractual parties are particularly important. Basically two aspects of such contracts need to be considered in IPS^2 concept development. On the one hand, an IPS^2 concept is explicitly determined by the assignment of property rights. On the other hand, the choice and design of the revenue model is crucial. As a purchaser of an IPS^2 is no longer necessarily the owner of its material components, a wide range of different possibilities to design revenue models are conceivable.

A revenue model is an heuristic model which addresses the measurable performance parameters for pricing as well as the value proposition of a business relationship and is therefore decisive for pricing (Hünerberg and Hüttmann 2003). According to Burianek and Reichenwald (2009) traditional and innovative revenue models can be distinguished from each other. Traditional revenue models that are based on the transactional sale of technical products or the offer of pure services (e.g., cost plus or fixed price) are cost-based and their price is measured by the expenses involved in manufacturing products or delivering services respectively. Unlike traditional revenue models, innovative revenue models are no longer characterised by incurred costs. Instead, their basis for pricing is determined by the realised customer benefit (a performance level or a performance result etc.). According to Burianek and Reichenwald (2009) three different types of innovative revenue models can be distinguished: i) usage-based, ii) performance-based and iii) value-based. These revenue models are planned to provide a more efficient risk distribution between contractual parties. This leads to new incentives for suppliers and customers alike. Thus, all this needs to be considered in the development of an IPS^2 concept.

2.1 Component Parts: The IPS^2 artefact

It is necessary to specify elementary constituents of an IPS^2. Rather than a standard comparison of product and service that is often inconsistent due to fuzzy distinctions between the both, a new construct is defined, the so called 'IPS^2 artefact'. To characterise IPS^2 artefacts five constitutive characteristics (specificity, dominant transformation, scale of integration, capability for partial substitution and connectivity) have been developed, whose detailed description is presented in Sadek (2009), Welp et al. (2008b), and Welp and Sadek (2008).

2.2 Basic structure of IPS^2

Next to IPS^2 artefacts that define the primary content of an IPS^2, the 'IPS^2 basic structure' (Sadek 2009) gives an overall view of an IPS^2. Furthermore, it serves as a constitutive basis for modelling and developing IPS^2 concepts. As shown in Fig. 1, the basic structure of an IPS^2 contains three essential components: i) influencing factors/surrounding conditions ii) the IPS^2 itself and iii) a dynamic target system.

The IPS^2 takes centre stage. As a transformation system or a controller respectively (Tan et al.

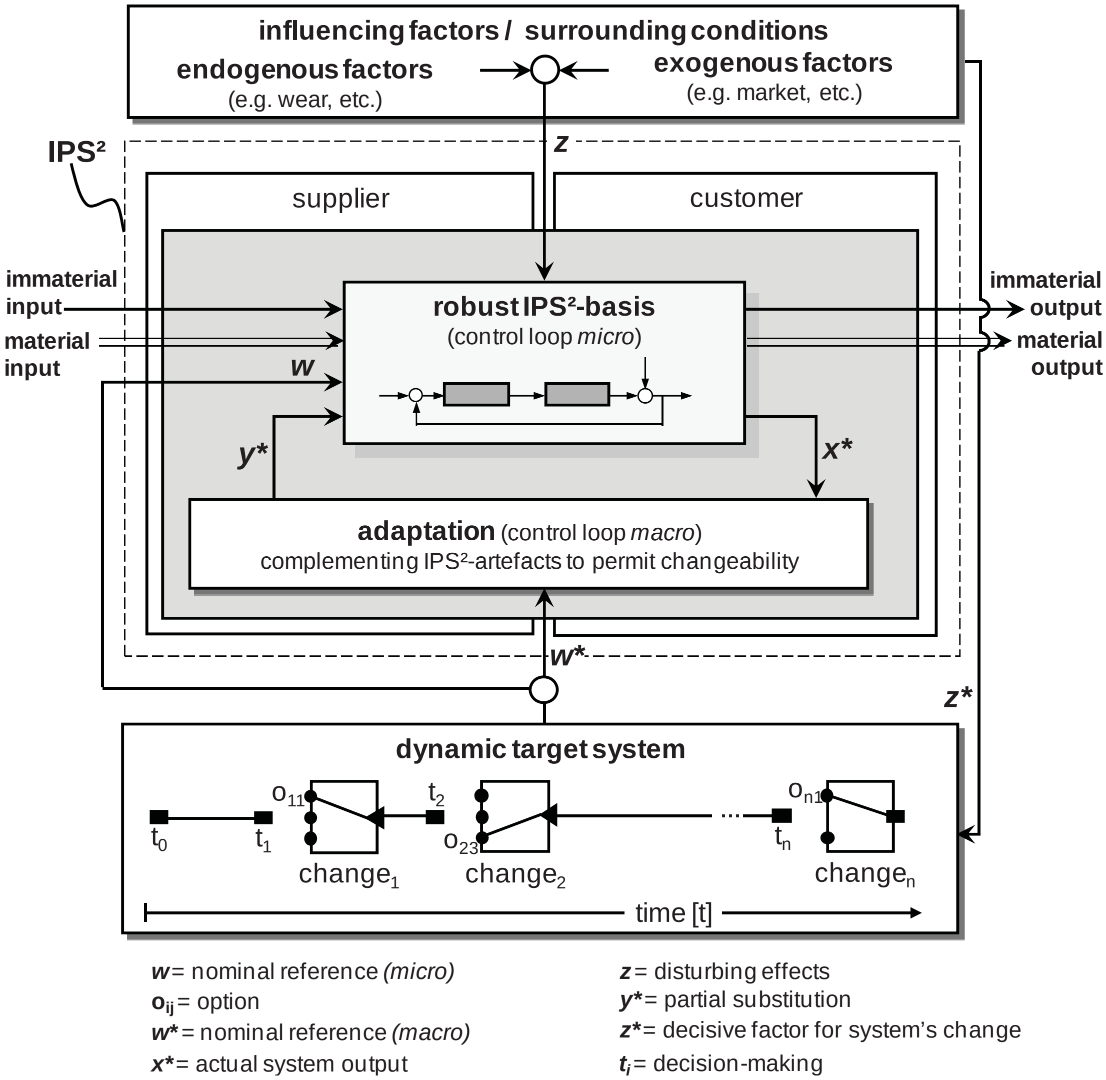

Figure 1: Basic structure of IPS²

2008) it should meet a nominal reference given by the dynamic target system (w or w*). Influencing factors or surrounding conditions (z or z*) cause negative effects and need to be compensated by the control system. The IPS² is separated from its system environment by a system boundary. The IPS² transforms immaterial input, such as labour or financial resources, in combination with material input, such as an unmachined part, into material output, such as a machined component. With that, an immaterial output, which equals performance in general, is also a result of this transformation process and is, therefore, part of the IPS² basic structure. A certain level of availability of a manufacturing system or a maintained machine component are examples of immaterial outputs. Supplier and customer who interact with each other during the transformation process are relevant stakeholders of an IPS². The transformation process itself is controlled by the dynamic target system. It contains different aspects of the business contract, especially all nominal references. To ensure the changeability of an IPS², a portfolio of options (o_{ij}) that can be defined in the business contract is specified in the dynamic target system. Options imply the right but not the obligation for the customer to decide in favour of future business decisions (Trigeorgis 1996). This implies as well discrete state changes of an IPS^2.

The robust IPS^2-basis is the core of an IPS^2, which can be compared to a controller in terms of cybernetics. In view of business-to-business market solutions, the robust IPS^2-basis equals a manufacturing system with its related human resources required to fulfil a certain task. The combination of IPS^2 artefacts, which constitute the robust IPS^2-basis, can be adjusted but cannot be exchanged completely. The robust IPS^2-basis is regarded as a micro control loop, which reacts to disturbing effects (z) without external interference. It is also capable to stabilise or optimise an IPS^2 according to the nominal references (w). However, due to economic restrictions the ability to adapt the robust IPS^2-basis to changes is restricted, so that it is not capable to react to all kinds of changes. To adapt an IPS^2 to extensive changing market conditions or customer demands an additional macro control loop, so called ‘dynamic adaptation’, is included. By partially substituting IPS^2 artefacts (y*) it is possible to implement alternative options. To take uncertain future events into account, options need to be considered already during the early phase of IPS^2 development. The feasibility of exchanging IPS^2 artefacts basically depends on their capability for partial substitution and their connectivity to related artefacts.

3 Conceptual Phase of IPS^2 Development

The conceptual design of an IPS^2 follows up the phase of strategic planning. Thus, business contracts are the basis for the development of IPS^2 concepts. Information about the contracted revenue model or the allocation of property rights is modelled together with specified requirements on a functional level. In this regard, using a functional description aims at reducing the complexity of the development task. Furthermore, the conceptual phase of IPS^2 development focuses on the determination and selection of principle solutions. As a result, the IPS^2 concept includes all selected principal solutions and describes the structural interaction between them as well as their logical functionality on a medium level of abstraction. Consequently, the interaction of service and product components during the value creation and usage is predetermined in the early phase of the IPS^2 development. An IPS^2 concept serves as a qualitative or quantitative basis to evaluate the system regarding technical and economic reference criteria. In addition, an IPS^2 concept is the basis for the subsequent design of IPS^2 modules and components.

4 Review of the state of the art

In a comprehensive study (Sadek 2009) existing approaches have been analysed, which support the development of multidisciplinary systems in general and of Product-Service Systems in particular. For the subject of multidisciplinary development methodologies different evaluation criteria have been defined (see Tab. 1).

Amongst others the fulfilment degrees with regard to ‘integration of product and service development’, ‘systematic multidisciplinary concept deployment’ or ‘determining product-service interdependencies in the early phase of development’ have been considered. A summary and comparison of the analysed approaches is shown in Tab. 1.

Despite an existing multitude of methodologies, this study unfolds that designers are only insufficiently supported by computer aided tools in the early phase of multidisciplinary system development. In terms of conceptual IPS^2 development, methods are missing for i) mutually determining IPS^2 artefacts, ii) integrating stakeholder’s preferences and iii) considering changeability of IPS^2. Nevertheless, some methodical approaches contain aspects that are significant for a model-based IPS^2 concept development approach. But currently no comprehensive integrated approach does exist.

Approach \ Evaluation cirteria	Degree of fulfilment in supporting... …a model based development of mulitdisciplinary systems	…a successive problem solving	…an integration of product and service development	…a systematic multidisciplinary concept development	…the determination of product-service interdependences in the early phase of development	…the interaction with customer's resources as well as the consideration of the dynamic IPS²-lifecycle
Systems Engineering (Bartalanffy 1969)	●●○○	●●○○	●○○○	●●○○	○○○○	●○○○
VDI 2221/2222 (VDI 1986) (VDI 1996)	●●○○	●○○○	●○○○	●○○○	○○○○	●○○○
Weber (Weber and Werner 2001)	●●●○	●●●●	●●○○	●●●○	○○○○	●○○○
Altschuller (Klein 2007)	●●○○	●●●○	●●○○	●●●○	○○○○	●○○○
VDI 2206 (VDI 2004)	●●●●	●●○○	●○○○	●●○○	○○○○	●○○○
Bender (2005)	●●●●	●●●○	●○○○	●●●○	○○○○	●○○○
Ramaswamy (1996)	○○○○	●○○○	●○○○	●○○○	●○○○	●●○○
Jaschinski (1998)	●○○○	●○○○	●○○○	●●○○	●○○○	●●○○
Kingman-Brundage and **Shostack** (1991)	●●○○	●●○○	●●○○	●●○○	●○○○	●●○○
Spath and **Demuß** (2003)	●○○○	●○○○	●●●○	●●○○	●●○○	●●○○
Aurich and **Clement** (2010)	●○○○	●○○○	●●●○	●○○○	○○○○	●●○○
Steinbach / Botta (Steinbach 2005)	●●○○	●●●●	●●●●	●●○○	●●●○	●●●○
Sakao/Arai and **Shimomura** (2004)	●●●○	●●○○	●●○○	●●○○	●○○○	●●○○
Thomas/Walter/Loos (Thomas et al. 2008)	●●○○	●●●○	●●●○	●●○○	●●○○	●●●○

Caption:
○○○○ = *low degree of fulfilment* ●●●● = *high degree of fulfilment*

Table 1: Review of approaches of multidisciplinary development

5 Heterogeneous IPS² concept modelling

To support the development of IPS² concepts, a novel modelling principle has been developed, the so called 'heterogeneous IPS² concept modelling'. It is particularly suitable for integrated product and service modelling, but it is also transferable to other multidisciplinary development issues. The integration ranges from the combination of various types of IPS² artefacts to linking model elements on arbitrary levels of detailing, abstraction and formalisation to form an IPS² concept model. A systematic and detailed deduction of this approach is described in Sadek (2009).

5.1 Theoretical Framework

As already mentioned in Welp et al. (2008a) and Welp and Sadek (2008), the definition of a generally applicable modelling space that is defined by three modelling dimensions (detailing, formalisation and abstraction) aids to constitute a harmonised comprehension of IPS² modelling (cf. Fig. 2). It is also used as a fundamental basis to decompose the heterogeneous modelling approach of mechatronics (Jansen 2007; Jansen and Welp 2007). This is necessary to partially extend the existing approach and to combine it with a new paradigm for integrated product and service modelling which is based on the definition of the IPS² artefact (see Sect. 2.1).

According to Sadek (2009), an IPS^2 is basically composed of a combination of IPS^2 artefacts that fulfill the required functions. Thus, the existential origin of an IPS^2 artefact is a function. According to Pahl et al. (2007) such a function is defined by a combination of 'noun' and 'verb' (cf. Fig. 2). In this context a noun represents the operand and a verb the operator of a solution element. According to mathematics an operand represents the structural basis of a function which can be transformed by an operator. Hence, an operand is determined by its possible state, whereas the operator is characterised by its ability to change operator's states.

The distinction between operand and operator is generally applicable to all types of functions. To use this as a generic principle for integrating different types of elements on a medium and lower level of abstraction rather than just as a functional description, the terms 'noun' and 'verb' are extended to the terms 'IPS^2 object' and 'IPS^2 process'. Whereas 'noun' and 'verb' constitute a function, the combination of 'IPS^2 object' and 'IPS^2 process' constitute an IPS^2 artefact. Thus, a functional, an object-related and a process-related development perspective can be distinguished.

An IPS^2 object equals the material or immaterial operand of an IPS^2 artefact that possesses definable states. IPS^2 processes complement IPS^2 objects. On the one hand, they can be regarded as operators that effect IPS^2 objects and their respective states (intra). On the other hand, IPS^2 processes are regarded as operators able to coordinate and to control the interaction of IPS^2 objects (inter). However, only the combination of IPS^2 objects and IPS^2 processes can generate a functional behaviour.

5.2 System coherent modelling planes

Based on the definition of IPS^2 object and IPS^2 process, a functional, an object-related and a process-related development perspective can be distinguished in order to fully grasp the complexity of heterogeneous IPS^2 concept modelling. This leads to the definition of three system-coherent modelling planes (cf. Fig. 2). A detailed characterisation of the modelling planes as well as the description of corresponding modelling elements and relations is described in Sadek (2009).

The transfer from planning an IPS^2 to its systematic conceptual development is carried out on the so-called IPS^2 function plane. An IPS^2 problem solution can be modelled abstractly and solution-neutral by defining and linking IPS^2 functions. A graphical, 2D representation is used to support intuitive modelling. Apart from modelling IPS^2 functions this plane is used to specify and model the distribution of risk that needs to be shared between customer and supplier regarding a business contract (Oliva and Kallenberg 2003). Therefore, the IPS^2 function plane is divided into the supplier and customer modelling zone. By placing an IPS^2 function in one of these zones, its related risk can be clearly assigned to supplier or customer. Both modelling zones are logically connected via a supplier-customer relationship. Content of the underlying business contract with relevance for IPS^2 concept development is defined in this meta-relation. This includes the distribution of property rights, the definition of the underlying revenue model as well as a certain portfolio of options, for instance.

The deliberately omitted concretisation of an IPS^2 problem solution on that plane is transferred to adjoining modelling planes. The IPS^2 object plane is intended for modelling a material or immaterial operand of an IPS^2 artefact. To model IPS^2 object structures effectively the IPS^2 object plane is represented by a three-dimensional modelling space. 3D modelling mainly results from modelling technical IPS^2 objects. Visualising IPS^2 objects by 3D elements improves the comprehension of IPS^2 object structures especially for interdisciplinary design teams. Furthermore, the model transfer from heterogeneous IPS^2 concept modelling to 3D-CAD design has been taken into

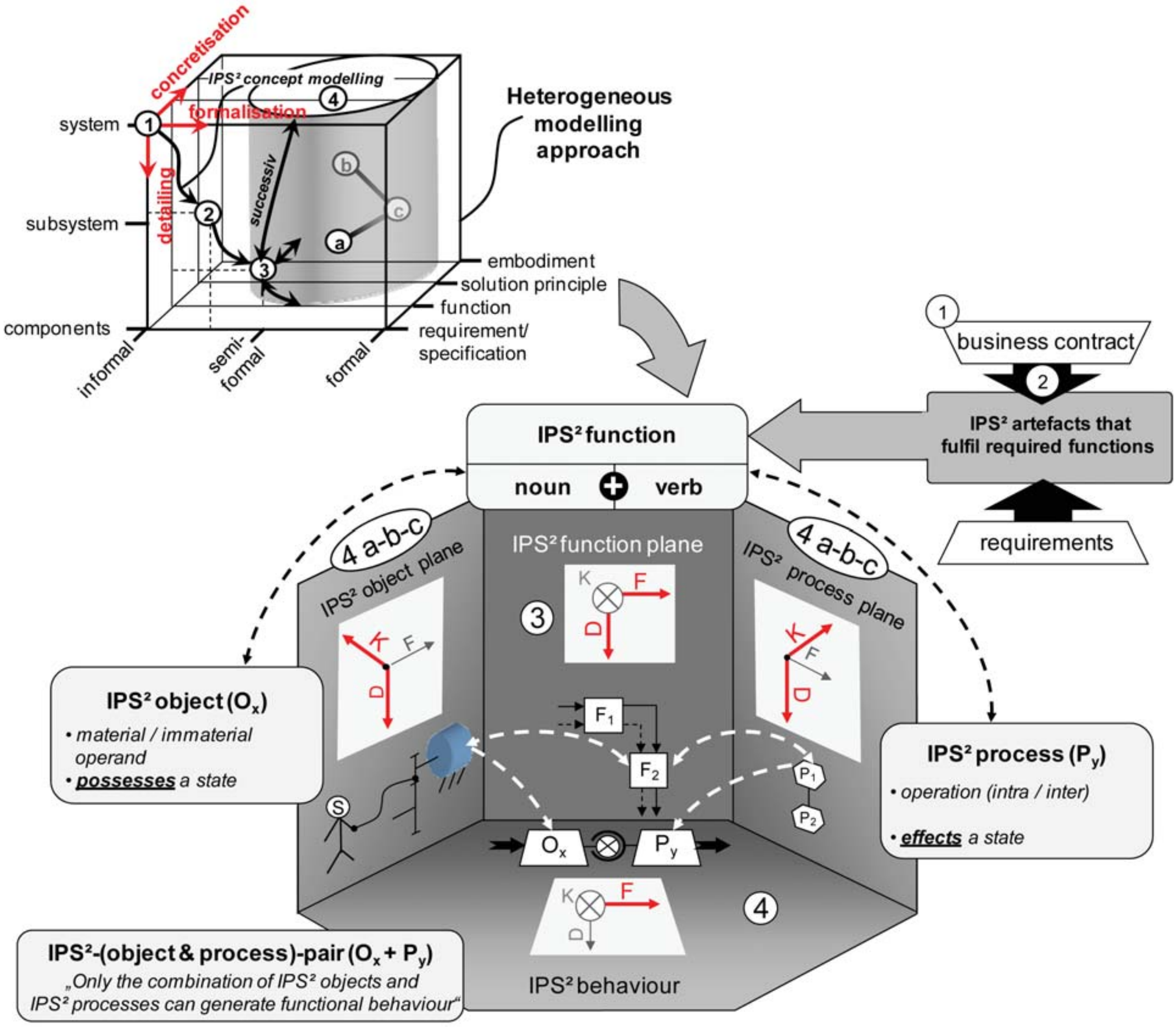

Figure 2: The theoretical framework for IPS² concept modelling

account. In contrast, the IPS² process plane has been defined to model intra- and inter operations that effect IPS² objects. IPS² processes are mainly graphically modelled using an IPS² specific activity diagram. The IPS² process plane is also used to model interactions between supplier and external factor (customer). Therefore, two modelling zones are defined and separated by a 'line of interaction'. In this case the line of interaction is equivalent to the correspondent line in Service Blueprints, according to Shostack (1984). The definition of these modelling planes enables an IPS² designer to develop IPS² concepts in a successive way. Step-by-step IPS² functions, IPS² objects and complementing IPS² processes can be developed. In doing so, interdependencies between IPS² artefacts can be determined in an early phase of development. The combination of all three modelling planes constitutes a heterogeneous IPS² concept model. Heterogeneous IPS² concept modelling aims at supporting IPS² designers to effectively represent different states of knowledge during the IPS² concept development.

6 Methodology for a model based development of IPS² concepts

In order to develop IPS² concepts in a systematic and efficient manner, it is necessary to elaborate an appropriate development methodology, which takes particular IPS² characteristics into account. Based on heterogeneous IPS² concept modelling, which enables an integrated description of IPS² concepts, a flexible process model will be introduced in the following paragraphs. On the one hand it comprises a problem solving cycle (micro-logic). It can be applied in all sub-steps during the development of IPS² concepts due to its generic logic. On the other hand, a superior guideline (macro-logic), permitting the temporal and logical structuring of the IPS² concept development process, will be introduced. Furthermore the proposal of rules, strategies and guidelines shall support the IPS² designer to elaborate process steps of the macro-logic.

6.1 Problem solving cycle (micro-logic)

The problem solving cycle for the development of IPS² concepts, displayed in Fig. 3, is based upon elementary mechanisms for problem solving. These are especially examined in connection with research in the field of systems-engineering (Ehrlenspiel 2007) and their principal validity is widely documented.

In order to incorporate the particular characteristics of IPS² and to adjust the micro-logic to IPS² concept modelling, certain modifications regarding the general problem solving cycle known from systems engineering (Haberfellner 2002) have to be made. The centre of the modified problem solving cycle consists of the in-teraction between functions, objects and processes relating to IPS² concepts. The internal dependency of their respective three modelling planes serves as a basis for a successive problem solving process, in which, based on a distinct problem, elements of the solution are identified and afterwards combined to a verifiable and assessable overall solution. Due to the causality between abstract IPS² functions as well as concrete IPS² objects and IPS² processes, the modified problem solving cycle especially supports the interplay of analysis and synthesis.

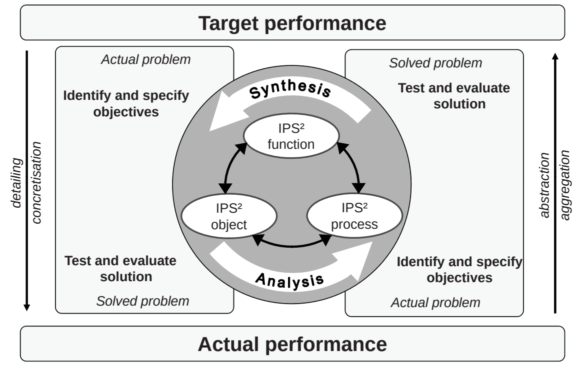

Figure 3: Problem solving cycle (micro-logic)

If a problem consists of the concretisation and detailing of a targeted performance, IPS² functions serve as an introduction to the synthesis of IPS² objects and IPS² processes. Their combination leads to IPS² artefacts. In a reverse way, the problem solving cycle can also be used for the analysis of an IPS² artefact. To do so, at first the IPS² artefact will be divided into IPS² objects and IPS² processes and afterwards abstracted and aggregated to an IPS² function, in order to identify the accompanying targeted performance. In respects of a flexible conceptual IPS² development process, modified problem solving cycles referring to the synthesis and analysis can be combined with or interlaced with each other in various ways to be suited to a particular problem.

6.2 Superior guideline (macro-logic)

The superior guideline proposed by Sadek (2009) is shown in Fig. 4. The macro-logic includes generally described sub-steps, which can be executed in the presented order to develop an IPS² concept.

The guideline should not be understood as a rigid 'development-corset' needed to be fulfilled, but rather as a flexible framework, adaptable to individual problems. Consequently, it is possible

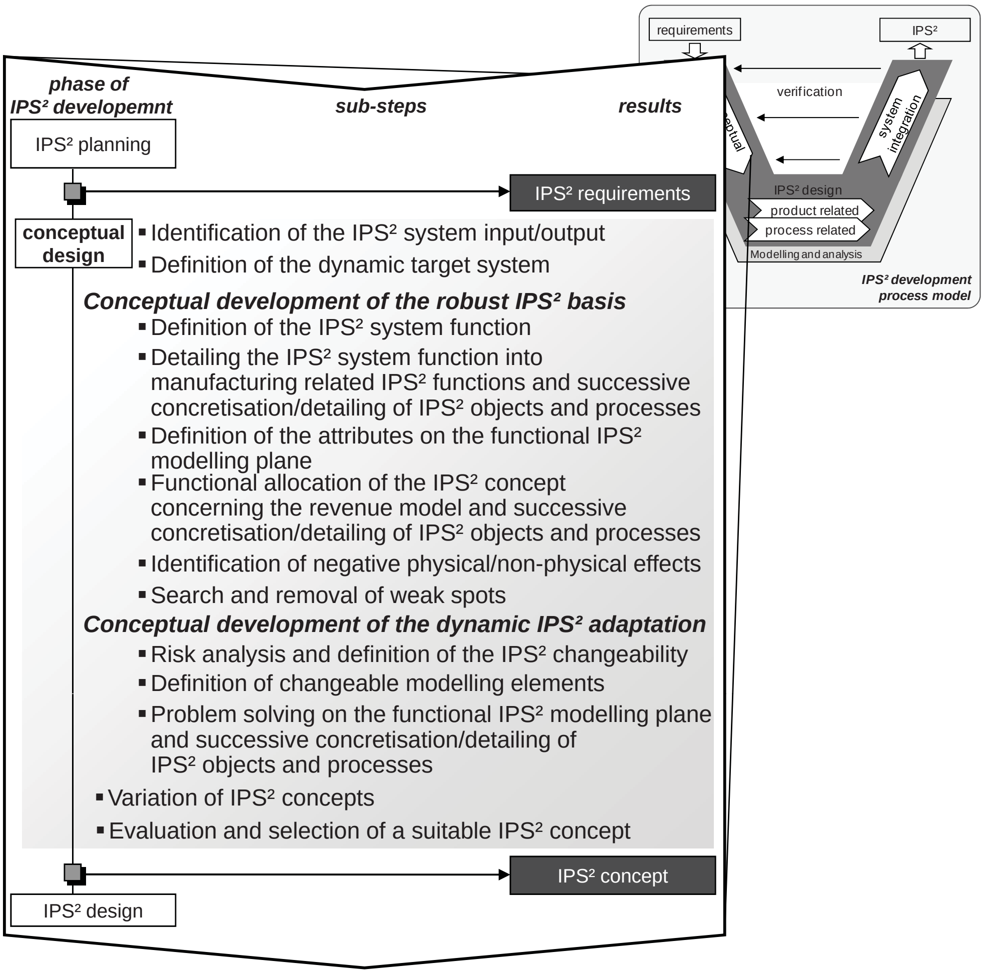

Figure 4: Superior guideline (macro logic)

to vary the order of the process steps, shown in Fig. 4, to emphasise certain aspects of the concept development or to neglect sub-steps, depending on the problem. After all, the introduction of this guideline aims at coordinating the development process of IPS^2 concepts more efficiently, reducing needless iterations as well as decreasing time involved with that. The sub-steps, described in the guideline address solely the phase called ‘conceptual design’, which is in turn an immanent element of the entire IPS^2 development process. Furthermore, the structural constitution of the guideline is based on the IPS^2 basic structure already being presented (see Sect. 2.2). Thus, there are primarily four elements: the IPS^2 system input/output, the dynamic target system, the robust IPS^2 basis and the dynamic adaptation.

In order to develop an IPS^2 concept, the system input that has to be transformed into the desired system output has to be identified at first. Moreover, the contractual terms concerning the IPS^2 have to be defined within the dynamic target system. At this point, not only the basic configuration of the IPS^2 has to be regarded, but also the portfolio of options agreed upon within the contract. Based on that, the next step of the guideline consists of the definition of the IPS^2 system function. It marks the beginning of the conceptual development of the robust IPS^2 basis. The complexity of the entire developmental task should initially be reduced and a stable situation for the consideration of system adaptations concerning the life cycle should be created. Especially, when developing a new IPS^2 concept, a 'TopDown' development strategy is to be recommended. Here, the determination of the solution is conducted from a holistic point of view, in order to propose solutions for the sub-systems and components as well as to educe sub-processes and process steps.

Consequently, the overall system's function of the IPS^2 has to be defined and successively detailed in manufacturing related functions. Using heterogeneous IPS^2 concept modelling, the developer is not restricted to extracting all of their ideas from the system's function. Rather, a mixture of generally required IPS^2 functions, IPS^2 objects and IPS^2 processes serves as a basis for the successive concretisation and detailing of the entire solution.

Heterogeneous IPS^2 concept modelling includes the possibility of characterising the supplier and customer in terms of their risk preference. Additionally, main aspects of the business contract can be modelled. Regarding the revenue model, functions are allocated to the supplier or to the customer according to their corresponding risk preference (see Sect. 5.2). The usage of the problem solving cycle allows the successive concretisation, or rather, the detailing of IPS^2 functions into IPS^2 objects and processes.

The 'robustness' of the IPS^2 basis is the focus in the following sub-steps of the guideline. For this, the endogenous and exogenous negative parameters affecting the IPS^2 have to be identified via appropriate methods. In the case of technical systems, the negative effects of human actors are often only of secondary importance and the physical effects on the system are prioritised. On the contrary, the conceptual development of the robust IPS^2 basis observes physical and non-physical effects equally. Thus, a close interdisciplinary cooperation is required in this sub-step in order to overcome notional obstacles. The heterogeneous IPS^2 concept modelling approach makes it possible to consider negative effects by using disturbance elements on all three modelling planes. They can be connected to the affected IPS^2 functions, objects and processes. This enables an effective search and removal of weak spots.

For economic reasons, not all changes of constraints, influencing factors and environmental conditions can be compensated by the robust basis of the IPS^2. Therefore, the development of a concept for the dynamic adaptation has to be conducted, which takes results of the previous process steps into account. Main restrictions are defined in the business contract. It contains references to required options defined by the customer. An option defines the possible reaction to certain changes with specified adaptations of the IPS^2. Depending on the information's dispersions between supplier and customer as well as the present knowledge about trends of the market and technology, options can be related to probabilities of occurrence. The probability that an option is chosen has to be determined. Therefore, risk analysis has to be conducted. Aiming at an overall maximisation of customer's and supplier's benefit, the strategic leadership of the conceptual IPS^2 development is faced with the decision to either fully consider the portfolio of options agreed upon in the contract or to take the risk of implementing an option in the provided IPS^2 during the delivery and use phase. This can result in higher costs. In order to make it possible for the IPS^2 to be changed, elements of the model have to be identified or defined, which are able to adapt the system.

In order to reach an overall optimum, solution elements or relations of an IPS^2 concept can be varied iteratively. Therefore, the last sub-step includes an evaluation of developed IPS^2 concepts. To introduce findings from subsequent sub-steps into the current IPS^2 development process, it may be necessary to incorporate iterations.

6.3 Rules, strategies and guidelines for the conceptual IPS^2 development

This paragraph proposes rules, strategies and guidelines to support the developer in generating and varying IPS^2 concepts. In addition to the exemplary elements shown in Fig. 5, Sadek gives an extensive view concerning essential rules, strategies and procedural guidelines (Sadek 2009).

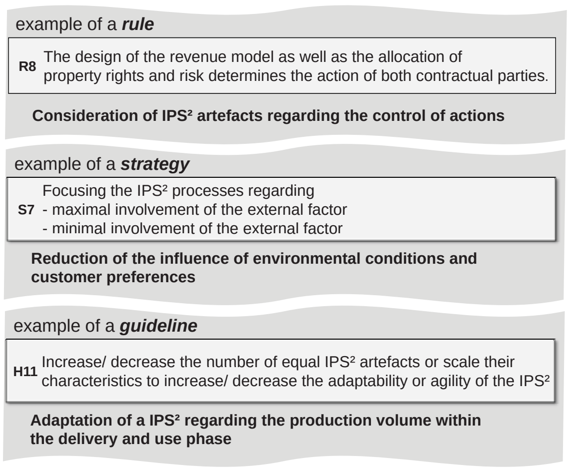

Figure 5: Examples of rules, strategies & guidelines

These rely mainly on the consideration of IPS^2 specific characteristics and on the special properties regarding the novel modelling approach. Due to their fundamental character, rules possess general validity during the development of IPS^2. In order to guarantee their general applicability, rules are described in a rather abstract way and can be interpreted by the developer depending on particular problems. In addition to rules, strategies can support the IPS^2 development process by defining essential targets in the heterogeneous concept modelling as well as render suggestions for the generation and variation of model relations. In this context, it is helpful to use contrary pairs of strategies, which provide extreme value parameters, due to their opposed aims. That enables an IPS^2 designer to solve certain development tasks systematically and to search for adequate solution compromises within the boundaries of the development scope. Furthermore, the expressed strategies should inspire the developer's creativity and present vital incentives for the development of alternative proposals. Unlike the rules and strategies, guidelines do not possess general validity. In fact, they target the stimulation of the creativity process and give the developer specific impulses for the differentiation of the dynamic target system, for the conceptual development of the robust IPS^2 basis and for the conceptualisation of dynamic adaptations.

7 IPS^2 concept development tool

Considering the IPS^2 development process, including the IPS^2 concept modelling approach with its associated development methodology and strategies, an adequate software tool is necessary to support an IPS^2 designer. Therefore, an integrated software tool has to provide functions for modelling as well as for methodical support. Both aspects are integrated in the architecture of the IPS^2 concept development tool, which is illustrated in Fig. 6.

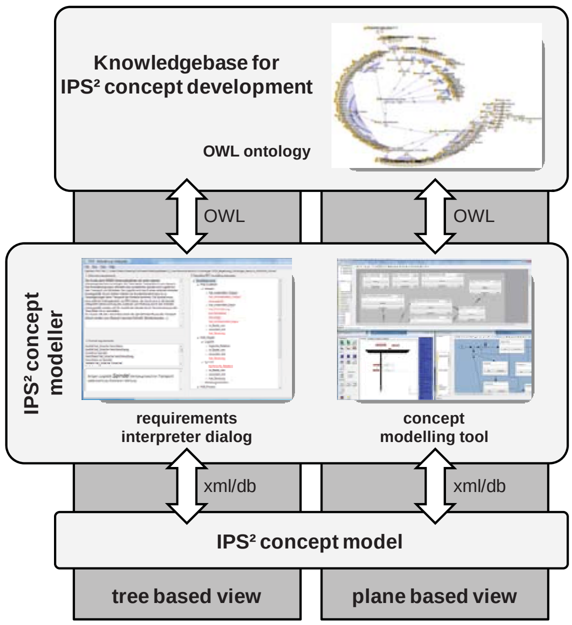

Figure 6: Architecture of the development tool

The software tool is divided into three major parts. The first part is the IPS^2 concept modeller, which provides a graphical user interface and a programming framework for plug-ins. The second part is the embedded methodical plug-in, which has access to the concept model data via an integrated database (db) and an XML interface. The plug-in also has access to an ontological knowledgebase. The knowledgebase itself is the third part of the IPS^2 concept development tool and is needed to describe basic knowledge for IPS^2 concept modelling and further knowledge for IPS^2 concept development.

7.1 IPS^2 concept modeller

The IPS^2 concept modelling tool offers two different types of model representations, a tree-based and a plane-based view. Figure 7 contains the so-called IPS^2 requirements interpreter dialog, used to derive an initial IPS^2 concept from informally described requirements, e.g., in the form of a text document.

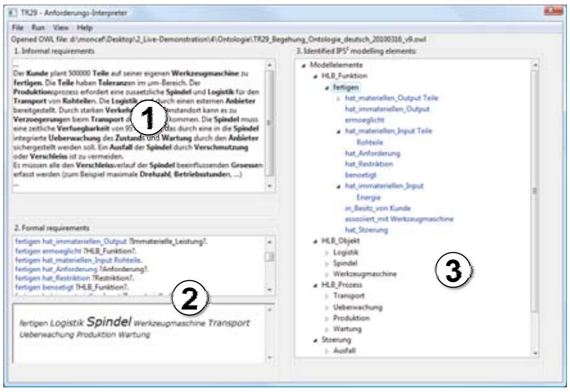

Figure 7: The IPS^2 requirements interpreter dialog

To derive an initial IPS^2 concept out of informal described requirements, the text document is loaded into the interpreter and is displayed in window 1. After assessing the document, single sentences of higher importance are displayed in window 2. By using the knowledgebase, the interpreter can automatically identify IPS^2 concept elements as well as their properties and relations. The results are displayed in window 3. The user can modify the initial IPS^2 concept by adding, removing or changing properties.

Tests with the IPS^2 concept modeller indicate that a tree based representation of the IPS^2 concept model is suitable to derive and modify single IPS^2 concept elements with their properties. Nevertheless, further research to improve the usability has to be conducted.

Figure 8 shows the graphical user interface for modelling on the IPS^2 concept modelling planes. The plane based representation of an IPS^2 concept is recommended for the further and more detailed development of an IPS^2 concept, because it allows a faster and intuitive modelling of new IPS^2 concept elements and relations on all three modelling planes. Therefore, the IPS^2 concept modelling tool provides a dedicated screen for each of the IPS^2 concept modelling planes.

The upper part of the IPS^2 concept modeller in Fig. 8 shows the IPS^2 function plane, with modelled IPS^2 functions as well as their relations. In the middle part, the screen represents the IPS^2 object plane. On this modelling plane a full 3D based modelling of IPS^2 objects is possible. The lower part of the screenshot shows the IPS^2 process modelling.

7.2 Knowledge-based assistance for conceptual IPS^2 development

In order to realise a knowledge-based assistance for conceptual IPS^2 development, the IPS^2 concept modelling tool is connected to an ontological knowledgebase. Using the knowledgebase enables the integration of the following three functions into the IPS^2 concept development tool:

- Identification of IPS^2 concept elements, properties and relations out of informally described requirements
- Suggestion of missing IPS^2 concept elements, properties and relations
- Verification of modelled relations between IPS^2 concept elements

These functions are achieved by speech recognition, which is used to incorporate different grammatical forms. The identification is performed in 2 steps. First, the interpreter dialog analyses each sentence in the text and identifies IPS^2 concept elements and properties through a comparison

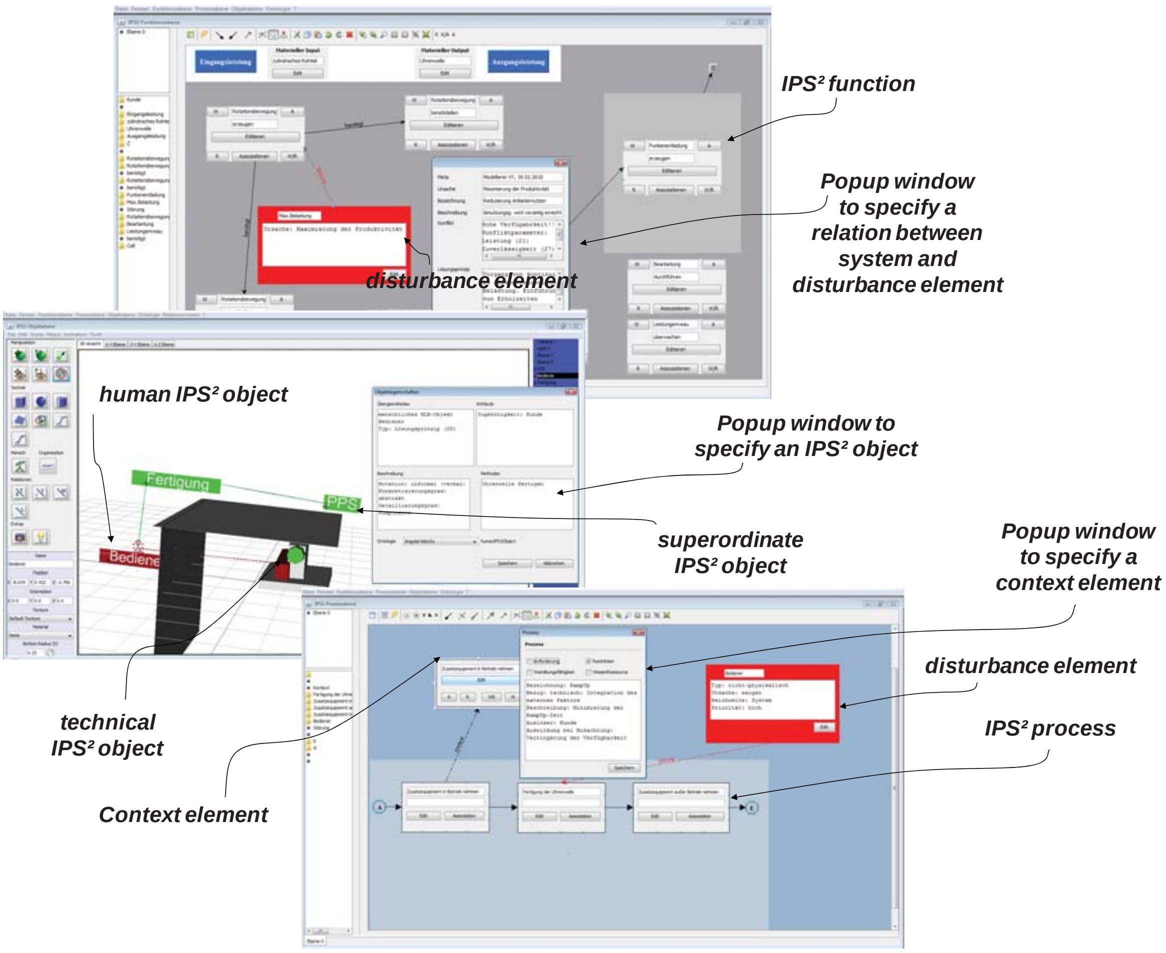

Figure 8: IPS² concept modelling tool

of the current model with the contents of the knowledgebase. In the second step the interpreter estimates all possible relations between IPS² concept elements and their properties as well as probably missing properties.

7.3 Knowledgebase for conceptual IPS² development

The ontological knowledgebase is modelled by using the Ontology Web Language (OWL) (Hitzler et al. 2008). The knowledgebase contains two major parts. The first part describes elements and relations of the IPS² concept model on a high level of abstraction. In accordance to Sect. 5 the basis for IPS² concept development is constituted by IPS² functions. For each IPS² function a certain number of requirements and restrictions as well as material and immaterial input and output can be assigned. The IPS² functions are associated with their respective IPS² objects and IPS² processes, which can be detailed and connected through appropriate relations.

The second part of the knowledgebase includes an element library. The element library is derived from this generic IPS² model description by defining subclasses of IPS² functions, objects and processes supplemented with restrictions on their relations. For example, a service technician is a subclass of the IPS² object 'human' and can only be connected to technical IPS² objects, e.g., a production system via a socio-technical relation.

An additional restriction could be the limitation on a specific type of production system. The knowledgebase is accessed by a common reasoning interface.

8 Evaluation example

To evaluate the computer-aided IPS² concept development approach, an IPS² specific issue which targets micro manufacturing systems has been chosen. In the following paragraph a suitable conceptual solution has been developed via the IPS² concept development methodology and the software tool to meet requirements and restrictions which have been elaborated to specify the problem of performance-based manufacturing of rotationally symmetric μm-parts. A process to meet the particular requirements of manufacturing rotationally symmetric μm-parts is Wire Electrical Discharge Grinding (WEDG) with rotating workpieces. The WEDG process is based on spark erosion, using wires as electrodes. To rotate the μm-parts relatively to the electrode, a conventional EDM-machine (electrical discharge machining) has to be supplemented with an additional spindle, which is integrated into the machine's workspace. The spindle also provides a workholding device for μm-parts.

8.1 Scenario description

A customer, who tries to enter niche markets by offering rotationally symmetric μm-parts, e.g., shafts in mechanical watches defines the following requirements:

- Req. 1: Rotationally symmetric μm-parts have to be machined on the customer's EDM-machine.
- Req. 2: Machining has to be performed by supplier's personnel.
- Req. 3: Demanded manufacturing volume can vary.
- Req. 4: Defined manufacturing time per part has to be observed (Maximising productivity).

Based on these requirements, the IPS² supplier defines the following restrictions:

- Res. 1: WEDG process is used for manufacturing rotationally symmetric μm-parts.
- Res. 2: Machine operator has got a certain qualification.
- Res. 3: Additional (material) IPS² artefacts, necessary to manufacture μm-parts, remain in IPS² supplier's ownership.
- Res. 4: Local and temporal availability is guaranteed.
- Res. 5: Technical availability is guaranteed.

Considering the abovementioned requirements and restrictions, a fictitious IPS² contract has been defined. It specifies the assignment of property rights for material IPS² artefacts as well as the revenue model. The IPS² supplier is owner of all additional IPS² artefacts, which are required for manufacturing rotationally symmetric μm-parts using the WEDG process. Thus, a problem solution in terms of classical product sales is basically not applicable (Res. 3). Not being the owner of the EDM-machine (Req. 1), the IPS² supplier disclaims the acceptance of risk for manufacturing defects resulting from the EDM-machine itself. By employing his own qualified personnel, the IPS² supplier is responsible for the quality of the manufactured output. Furthermore, it can be deduced from Req. 3 that the customer's benefit can be increased by a local and temporal provision of additionally required IPS² artefacts. By guaranteeing local and temporal availability of x% the IPS² supplier takes the associated risks, e.g., costs resulting from downtime. To maximise manufacturing productivity the IPS² supplier tries to prevent downtimes of the provided technical equipment by him to the customer. To share the risk he defines a technical availability of x% for the provided means of production (see Res. 5). In consequence, a 'performance based revenue model' is defined.

8.2 Identification of IPS² system input/output

An entry to the conceptual development of the IPS² is formed by specifying the IPS² system's input and output (cf. Fig. 9). A cylindrical raw part,

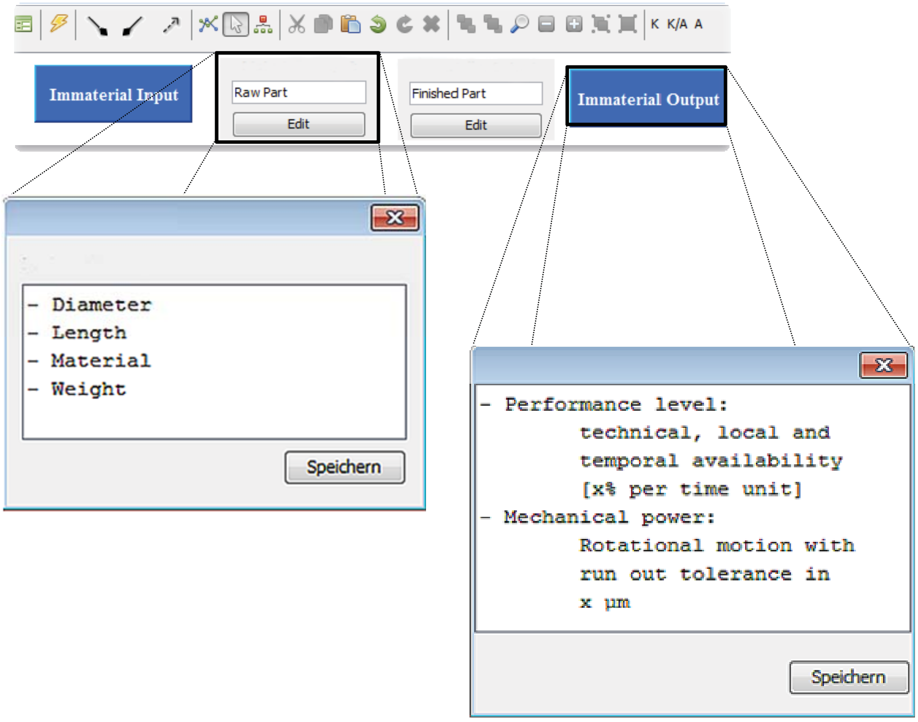

Figure 9: IPS² system inputs and system outputs

attributed by diameter, length, material etc., is defined as material input. The result of the manufacturing process, the 'finished part', is specified in the modelling element 'material output'. In addition to geometrical attributes, manufacturing related properties are defined in this model element. Immaterial input for the transformation of raw parts into finished parts is provided in form of financial resources, electrical power and labour. Besides the material output, the IPS² also generates an immaterial output. In the designated modelling element 'immaterial output' local, temporal and technical availability as well as the mechanical performance are specified.

8.3 Conceptual development of the dynamic target system

The target values which are defined as IPS² system outputs are also an inherent part of the dynamic target system. Moreover, the portfolio of options agreed upon within the contract is defined within the dynamic target system.

To limit the complexity of the evaluation example, only one option will be considered. With this option the customer gets the possibility of replacing the machine operator within the delivery and use phase. Thus, the machining could be performed by the customer himself instead by the supplier's personnel.

8.4 Conceptual development of the robust IPS² basis

Following the superior guideline the next substep of the development of the IPS² concept is the development of the robust IPS² basis. The transformation of input into output requires an IPS² system function, which describes the overall performance on the lowest level of detailing (cf. Fig. 10). In the beginning detailing the IPS² system function is based on the development of manufacturing related sub-functions. These functions enable the transformation of material input into material output. After that, functions to generate the desired immaterial performance level

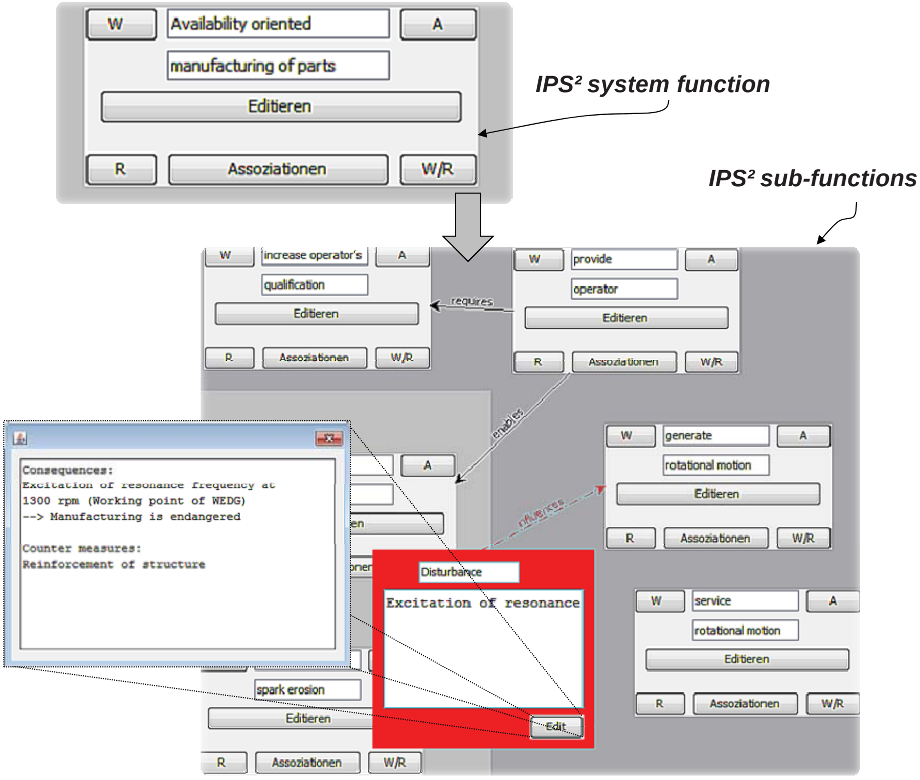

Figure 10: IPS² functions

are developed. To manufacture rotationally symmetric µm-parts, the customer's EDM-machine will be temporarily supplemented with an additional spindle, which is portable and integrated into the machine's workspace.

Besides the technical IPS² artefacts and the machine operator needed for manufacturing µm-parts, additional human and superordinate IPS² artefacts are required. To guarantee technical availability, a service technician is needed for maintaining the spindle. Furthermore, the maintenance has to be coordinated by an adequate superordinate IPS² artefact. To guarantee a local and temporal availability, the superordinate IPS² artefact logistics is required to coordinate and accomplish the transportation of the spindle.

8.5 Conceptual development of the dynamic IPS² adaptation

The IPS² has to allow its dynamic adaptation to changing restriction or influencing factors. In this evaluation example, the changeability of the IPS² has to be considered by the possibility of replacing the supplier's personnel through customer's personnel during the manufacturing process. Hereby, the operator's qualification influences the manufacturing process significantly. The change of risk allocation is combined with the change of the machine operator. The customer takes the risk for machine operation. To integrate less qualified machine operators, additional IPS² artefacts have to be added, e.g., an 'operator training'.

In Fig. 11 the IPS² object plane and the IPS² process plane are shown.

An increasing spindle wear that is associated with the replacement of the operator, requires additional components for condition monitoring. Thus, a condition monitoring equipment has to be integrated as well as additional sensors to measure the condition of the spindle. For a

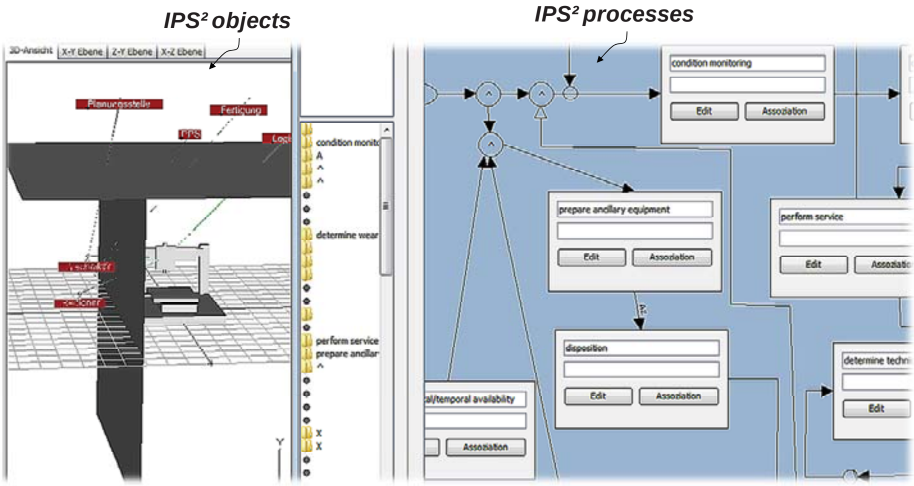

Figure 11: IPS² objects and IPS² processes

condition-based maintenance the condition monitoring
equipment has to communicate the machine data to the maintenance organisation.

9 Summary and Outlook

IPS² is a problem solution for B2B market issues and targets a long-term customer-supplier relationship. Taking interdependencies into account already in the early phase of IPS² development is especially important to ensure the synergetic interaction of IPS² artefacts during their entire life cycle and to offer an integral customer specific solution. Thus, based on the heterogeneous modelling approach, a model based methodology for conceptual IPS² development has been proposed. To show its feasibility, it has been implemented as a software prototype and evaluated based on an IPS² specific issue from the field of micro manufacturing.

Future research needs a further development and optimisation of the software tool and the design methodology. During conceptual IPS² development, the IPS² designer has to make a lot of initial design decisions. These decisions affect the entire subsequent design process significantly. Especially the desired flexibility of an IPS², which is very important in terms of long-term customer-supplier relationships as focused in the new business models, causes particular difficulties in making decisions. To provide flexibility in an uncertain environment the IPS² has to allow its dynamic adaptation to changing restrictions and influencing factors during its life-cycle. Therefore, a changeable architecture of the IPS² is necessary and hereby connected design decisions under uncertainty already have to be made in the early phase of IPS² development. Therefore, an adequate methodical framework to support decision making under uncertainty has to be developed, which considers economic as well as engineering properties.

Furthermore the development of a model-based approach for domain allocation is aspired. Based on the heterogeneous IPS² concept modelling approach, the deliberate and explicit choice of domains (here technical products and industrial services) as well as their combination to IPS² is focused. The aspired methodology should support a designer to create and vary IPS² concepts systematically. In this context, IPS² specific premises, for example the maximisation of the overall benefit, as well as specific views on IPS² concept development, such as the product/process-integration, will be considered.

Considering the IPS^2 concept development tool, improvements of the software prototype can be separated into three different aspects. First, improvements of the graphical user interface are necessary. The graphical user interface is designed to provide essential functionality for IPS^2 concept modelling ignoring a possible information and interface overload for the user. A better form of representation has to be found. The second aspect is the improvement of the knowledge-based assistance. The concept modeller is capable of providing an adequate support for concept modelling in terms of model verification and completion but does not provide functions for more efficient modelling. The improvement of both aspects has to consider practical user experiments, which have to reveal the specific limits of the software prototype. The last aspect is the integration of the concept modeller in a more complex development environment. In this regard, a suitable data exchange with Design for X (DfX) software and Product Lifecycle Management has to be developed.

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