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New PSS design method of a pneumatic energy system

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Abstract

Most existing methods supporting the design of Product-Service System (PSS) support the ‘conceptual design’ phase at the higher levels of abstraction and the technical design phase strongly lacks of methodical support. This can be explained by the existing challenge of coupling products and services in design since these two perspectives currently focus on different aspects and use specific models which appear as difficult to integrate. This paper proposes the design of a PSS for a pneumatic energy delivery system. The design is based on the combination and adaption of two existing methods from the product- and service-oriented design approaches for system engineering. Three levels of description are adopted: external and functional level, process level and structure level. Different models are used to illustrate the levels. Their ability to reconcile the product- and service-oriented approaches is discussed since they provide a comprehensive view of the system in both perspectives. The resulting design process allows the identification of component specifications and can be iterated at several levels of detail. This case-based design illustrates how the PSS design process can be supported at the technical phases.

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Keywords: PSS design ; case study ; models ; system approach ; product-service integration

1. Introduction

Product-Service Systems (PSS) design is claimed to require research attention to develop or to reinforce existing methodologies [1]. The main problem is that PSS design covers the two distinct fields of product and service engineering. The integration of product and service design approaches is difficult since these processes are currently performed by different staffs with different skills and expertise [2]. Proposals that achieve a full integration of product- and service-oriented approaches in a system view are somewhat missing, which leads to major difficulties for supporting the detailed phases of PSS design. A common taxonomy of the steps needed to engineer a PSS is not yet available [3]. However, most of them encompass the needs analysis and requirements identification which can be integrated or separated of/from the concept creation, the identification and integration of the sub-systems required, and a modelling phase which can play several roles [3] [4]. The sub-system identification and integration usually starts by identifying the system functions and features expected before allocating them on sub-systems. The sub-systems interactions are currently supported by process-based models in service approaches while product engineering proposes models more oriented towards the physical aspects.

This paper proposes the design of a PSS for a pneumatic energy delivery system. The design basically combines two existing design methods: one is a product-centered PSS design method [5] while the other is a service design method [6]. The resulting design is oriented towards a system perspective, with different levels of description. Three levels of system representation are explored: external and functions level, process level and structure level. Different models that illustrate these levels are examined and discussed so as to facilitate the reconciliation of product- and service-oriented approaches providing a comprehensive view of the system. The result facilitates the identification of component specifications and can be iterated at several levels of detail.

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The paper is organized as follows. The next paragraph aims at providing an overview of the two design methods which are then applied to the industrial case described in paragraph 3 which follows the proposed decomposition levels. Iteration at the sub-system level and perspectives are briefly discussed in paragraph 4. A conclusion is then drawn on the major interests and perspectives of this method for PSS design.

2. Overview of the two PSS design methods

2.1. Defining the system

In this work, a PSS is understood to be a set of components and their structure organization.

The components (or sub-systems) can be either physical products or service units. A physical product is a tangible object and a service unit is a structured entity of the provider organization and can then be considered as a 'department' within a company. The definition of components encompasses the concept of 'infrastructure'. Infrastructures are defined as components shared for several uses (not necessarily designed only for the considered system) which can be pre-existing. They can be physical products (for example electrical installations) or service units (human resources management unit). The 'structure organization' corresponds to the organization of component interactions to provide system functions and activities.

2.2. PSS design

The design of the system combines common features of two product and service approaches in order to provide engineering methods based on system design.

The first one is the product-oriented framework proposed by Maussang et al. [5] which integrated a system approach to facilitate the design of physical products in a PSS context. The second one is the service architecture proposed by Luczak et al. [6] for service conception. Both of these frameworks decompose the system description into three levels: the external and functional level, the process level and the structure levels.

The external and functional level aims at providing the system's goals. The study of the system's interactions with external elements supports the identification of the external functions or features expected in the system External functional analysis is used in the product approach [5] while a more service-oriented model called Blueprint-based Model (BBM) is proposed for the service perspective. Both these models identify:

- the identification of the external elements
- the identification of the system's boundaries which can be physical or intangible
- the identification of the system's interactions with the external elements

The study of the system's interactions with the external elements should lead to the identification of the functions or attributes expected in the system. A functional model based on the Functional Analysis System Technique (FAST) decomposition is used for refining the external functions into internal (or technical) functions [5]. The functions have to be defined by identifying the major contexts. These contexts correspond to established 'situations' where a set of state variables of the components are defined and stabilized. The transition between contexts corresponds to "events" or state changes of external elements or of components. Each function has to be fulfilled in all the identified contexts.

The process level corresponds to the description of the 'stimuli-responses' phenomena occurring in the system. The 'functions delivery process' corresponds to the sequential organization of the activities necessary to provide the functions. Structured Analysis and Design Technique (SADT) can be used to describe the 'activity scenarios'. An activity scenario corresponds to the complete sequence of activities which are necessary to achieve a function (sub-function) in a given context. The assembly of scenarios should identify: the time-sequence organization of scenarios in each context; and the time-sequence organization of each context by identifying the transition variables.

Structure models describe the organization of the components within the system. Two structure models can be used. A product-oriented view uses the Functional Block Diagram model [5] which complies with a 'physical view' of the system. A service-oriented structure model (BBM) represents the intangible system boundaries and the repartition of component roles to realize the activities.

This paper proposes to combine and adapt the two methods and apply them to an industrial case study presented on the following paragraph.

3. A pneumatic energy delivery system

The method is tested on a pneumatic energy delivery system to explore how the specifications of the products and the service units and their interactions can be identified.

3.1. Introduction of the case

The PSS provider offers a pneumatic energy delivery system to his customer through long-term contracts. The PSS customer is an industrial company specialized in the manufacturing of compressors used for refrigerating systems. The customer needs the pneumatic energy to supply his production engines continuously with expected levels for quantity, quality and availability. The PSS system then comprises a compressed air plant associated with technical services like maintenance and repair services and remote monitoring of the equipment.

3.2. Identification of the external elements

External analysis identifies the external interactions the system has with external elements. This must lead to the identification of the external functions and attributes expected. An audit performed by the provider identifies the external elements of the system and the initial major 'contexts' to be taken into account.

The compressed air plant is supplied with electrical energy which is not under the provider's responsibility. The compressed air produced by the plant is delivered to a pre-existing piping network which transports the pneumatic energy to machines for material shaping. The customer is responsible for up-keeping its own piping network. The plant is located in the customer's premises in an accessible spot for the customer's technicians can access because of the presence of other equipment.

Main contexts, linked to different events, are then identified. The context called 'usual functioning' refers to the current plant functioning. However, the electrical energy supply can fail or the customer's piping can be damaged leading to leakages. A drop of the external temperature of air can freeze the pipes. Technicians can also enter in the premises. All these contexts have to be identified in order to define the responsibilities of each stakeholder and then the system's functions in each context.

3.3. The service-oriented model for external analysis

The service-oriented model uses the BBM notation and allows the identification of the intangible boundaries between the stakeholders (corresponding to interaction and visibility lines) and their respective roles. A partial external BBM is shown in Fig. 1.

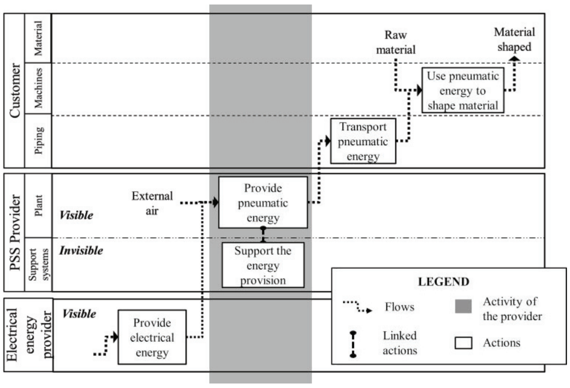

Fig. 1. External Blueprint-based model (partial view).

It displays the main activity of the PSS provider in the context of 'usual functioning'. The plant must provide pneumatic energy and support systems for energy provision are required although not yet defined. Actions performed by the customer's elements and by the provider of electrical energy are also shown. Other BBM can be built to describe the other contexts and could display for example the potential interventions by customer technicians on the equipment.

3.4. The product-oriented model for external analysis

In a product-oriented view, the system is considered as a black box and provides functions to the external elements that can be Interaction Functions (IF) or Adaptation Functions (AF). A partial view of the external functional analysis model is presented in Fig. 2 which also reflects the 'usual functioning'. The main function is the IF 'Use external air and electrical energy to continuously supply pneumatic energy to the customer's pipes'. This paper will only detail the function IF1, other AF are shown as an indication.

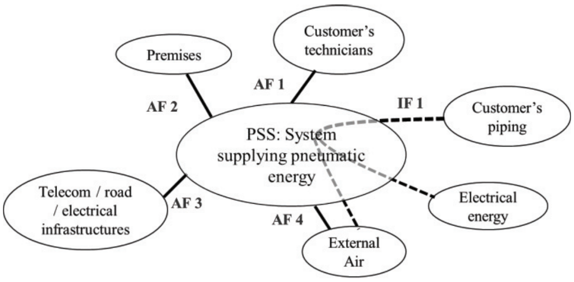

Fig. 2. External functional analysis (partial view).

The main function described in the FBD corresponds to the main activity displayed in the BBM. However, different types of information are provided in these two models. The BBM is somewhat more oriented towards illustrating how the system interacts to realize the activities by decomposing the roles between the system and the external elements while the FBD focuses on the physical interactions of the system with the external elements.

3.5. Functional decomposition

IF1 is decomposed by using the FAST technique. Principles for solutions (products and service units) are associated to each technical function. At the first level of decomposition we define two technical functions for IF1: TFA and TFB. TFA 'to perform the pneumatic energy supply' is accomplished by the products of the compressed air plant but will not be developed in this paper. The second technical function TFB 'to ensure the availability of pneumatic energy' is decomposed into several sub-functions. Only two sub-functions are presented in this paper (see Fig. 4). The provider is continuously informed of the plant state (TF1) through remote monitoring (TF1.1) and failure detection and diagnosis (TF1.2). Such sub-functions are realized by using a Remote Control and Monitoring System (RCMS) associated to software linked to a computer interface (called C&S for computer and software) and to cell phones used for alerting a supervision team responsible for diagnosis.

The guarantee of air availability requires the development of a failure mode and effects analysis (FMEA) which should support the refinement of contexts identification. To simplify the understanding in this paper, only one type of event is taken into account: compressor failure which corresponds to a stop of a main compressor. The continuity of air provision is ensured by TF2 and requires one function (TF2.1) to ensure the air compression by a reserve compressor and another function (TF2.2) for repair operations by a technical team.

All the technical functions are decomposed through a means-end axis which traces the organization of 'goals'. The activity scenarios that detail these functions help to clarify and understand the organization of 'stimuli-responses'.

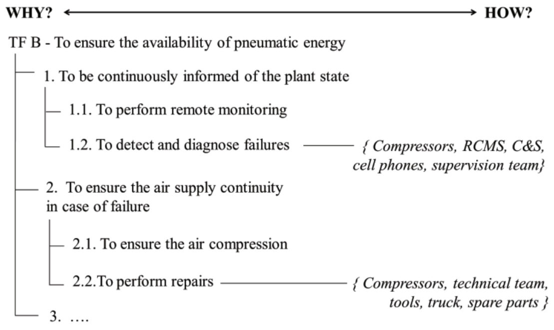

Fig. 3. FAST decomposition of the Interaction Function (partial view).

3.6. Process modelling

A partial view of an activity scenario associated to TF 2.2 is presented in Fig. 4. This repair scenario (TF2.2) can only start with the output information flow of the failure detection scenario (TF1.2). The diagnosis of the failure is performed by the supervision team, who informs the technical team (TF1.2). These two scenarios are then linked by an output/control relationship which means that the output of the last activity of the TF 1.2 scenario is a necessary condition for starting the TF2.2 scenario. In the TF2.2 scenario, the technical team moves to the customer's premises and starts the repair operations with the compressor dismantling before replacing the spare parts.

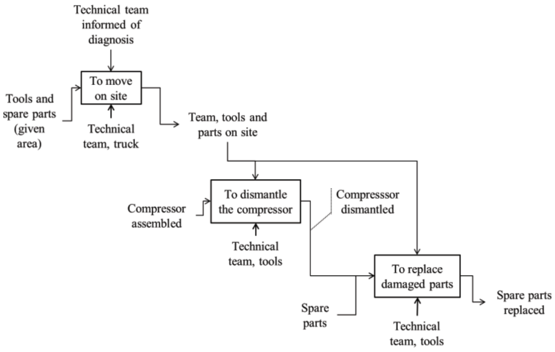

Fig. 4. Scenario of activities for TF2.2 (partial view).

This example shows how the activity scenarios can be defined for each technical function. The scenarios are assembled together in a time-sequence (TF1.2 and TF2.2 are assembled by an output/control link) to form the entire 'functional delivery process' of the system in all the contexts identified. The activity scenarios correspond to the organization in time sequences of the activities which differs from the organization of goals provided by FAST that decomposes the functions through a means-end axis. The activities scenarios can be described without detailed information on the entities realizing the activities. The structure models describe the organization of the components within the system.

3.7. The product-oriented structure model: FBD

Fig. 5 partially shows a partial view of the FBD model of the system. The two thick black lines at the top and the bottom correspond to the physical system boundaries. The ovals represent the external elements. Inside the system, the rectangular boxes are used for representing the products and the curved-angles boxes for the service units. The flows are represented by the thick dotted lines and the involvement in activities by the curved thick lines of the design buckles. Thin black lines represent the physical contacts between components. To avoid an overloading of the scheme, physical contacts with the external infrastructures are represented by a letter index and for the same reason; the energy flows are not represented here.

The circulation of information from the compressor to the technical team corresponds to the failure detection diagnosis and communication by the supervision team (TF1.2). The design buckles and other flows represent the activities of the repair scenario (TF2.2): (a) move on site; (b) dismantle the compressor; (c) replace damaged parts.

The FBD is useful to understand the physical organization of the components.

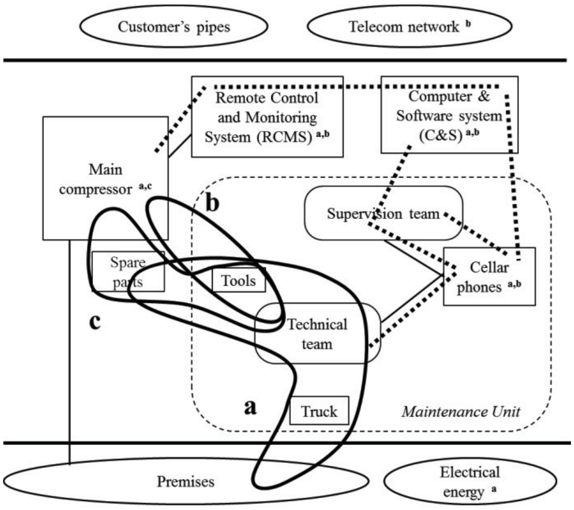

Fig. 5. Functional Block Diagram (partial view) of the system.

3.8. The service-oriented structure model

A partial view of the BBM is shown in Fig. 6 which also represents the repair scenario (TF2.2). Each activity of the scenario (a, b, c) has been decomposed into linked actions. As in the FBD the energy flows are not represented here. The actions description illustrates component interactions in the activities by decomposing these activities into actions. Actions are defined as the effect that an entity (external or system component) exerts on one another. An action has a subject, i.e. the entity that exerts the action, and an object, i.e. the entity that is acted on. Actions can have reciprocal influences and can then be defined as 'linked actions'.

For example, considering the activity "to move on site", two components are considered as performing the activity in the SADT model: the truck and the technical team. They both are necessary for transforming the physical locations of the spare parts. Their "roles" or respective actions in the activity can be expressed as follows:

- The action "drive" exerted by the technician (technical team) on the truck.
- The action "transport" exerted by the truck on the team and on other equipment.

The reciprocal states transformations occurring on the team and truck are not shown for simplification. The 'actions' relationship is sufficient to provide a comprehensive view of the objects and subjects of the two transformations.

The BBM model is useful to show the exchanges of flows between the components, their respective roles or responsibilities in the service delivery process through actions and the time sequence of these transformations.

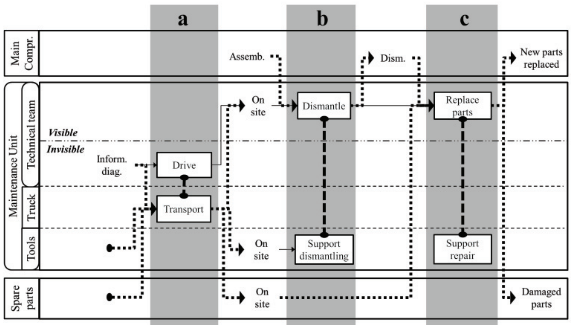

Fig. 6. Blueprint-based model (partial view) of the system.

3.9. Structure models complementarity

The FBD is oriented towards the physical organization of the components whereas the BBM is focused on the service delivery organization. Consequently, these two structure models display complementary information about the component's interactions.

Firstly, complete information of component interactions cannot be displayed by each model. The FBD model allows illustration of the physical contacts but not the roles links whereas the BBM allows showing these links but not the physical contacts.

Secondly, the BBM emphasizes on the organization of activities in time whereas the BDF emphasizes on their organization in space. To perform travel activity (a) realization for example, the FBD clearly shows the link physically created by this activity between the system components involved and the external element 'premises'. In the BBM, this space consideration does not appear. On the contrary, the BBM shows the sequential relations which exist in time between the activities: the travel is seen as previous activity for dismantling and parts replacement because of the necessity for the involved components to be in a given state (on-site). However, this sequential organization is not displayed by the FBD.

Thirdly, for a same activity realization, the two models can provide different information for product- or service-oriented approaches in design. For example for providing the spare parts replacement (c), product- and service-oriented views can be adopted for the design of the components involved. In a product-oriented view supported by the FBD, the spare parts replacement consists in the creation of physical contacts between for example the parts and the compressor. The emphasis is then put on the compliance that should exist between the spare parts and the damaged parts within the compressor. Are the new spare parts technologically compatible? This leads the product designer to focus on the necessary components of the compressor. In a service-oriented view supported by the BBM the spare parts replacement also consists in a material flow which is transformed by sequential actions that have to be provided. The emphasis is, here, put on the transfer of material that should be organized in time. Are the spare parts immediately available (and ready for transportation) when a compressor fails? This leads the service designer to identify the necessary support processes and resources to accomplish the spare parts replacement activity.

These two structure models are complementary for representing the PSS in a system view since they allow modelling of the system's components and their 'structure organization' by adopting both physical and service delivery perspectives.

4. Iteration at the sub-system scale

We propose to briefly explain how the method can be iterated at the component scale and how the previous structure models support this iteration.

4.1. Product specifications and refinement

By using the two structure models the physical products can be considered as sub-systems on which the method can be iterated. The FBD helps understanding the relationships between the product and the external elements in a physical way. As shown by Maussang et al. [5] this can support the iteration of the external functional analysis at the product level. Fig. 6 shows a partial view of the external functional analysis of the compressor in the context of a failure.

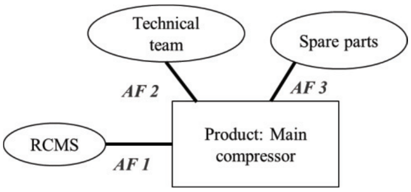

Fig. 7. External functional analysis of the compressor (partial view) in the context of a failure.

The product specifications can then by displayed. For example in Fig. 6, the compressor has to:

- AF1: enable the failure detection with the remote monitoring system

- AF2: be easily dismantled by the technical team
- AF3: having parts easily replaceable

These specifications can be refined by successive iterations which lead to the identification of the compressor's components.

4.2. Service specifications and refinement

Using the BBM, the service unit specifications can also be defined. Specifications can be seen as skills or necessary resources. For example, the technical team has to be able to:

- drive the truck
- dismantle the compressor by using the tools
- replace the compressor's parts

Refinement during design of a component supports refinement of the design of the interacting components. For example, refinement of the compressor's components can lead to refinement of the technical team's actions in a more detailed BBM. The method supports the concurrent design of these components. However, refinement of a service is not systematically turned towards an internal view of the service unit: it can consist in the identification of external elements as support processes and external events affecting the service delivery realization. This explains the fact that a black box representation is not suited to service specifications.

In the case study, the BBM expresses the necessity for the spare parts to be "available" when a compressor fails and to be ready for transportation. The role of the service designer is to organize the process in time by defining the necessary roles within the provider's organization and roles of external stakeholders. The spare parts availability implies the definition of the necessary support processes and resources. A service unit called the 'equipment supply unit' and the spare parts provider both have actions to perform in this process. Fig. 8 shows a part of the BBM which has to be defined for organizing service delivery.

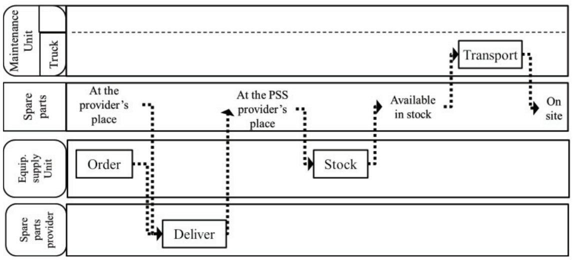

Fig. 8. Blueprint-based model (partial view) of the system.

The supply unit has to order the parts which are delivered by the parts provider before the supply unit stocks these parts.

The service designer is here interested in providing a planning adapted to the logistic aspects of the spare parts provision. Contrarily to the product which is refined by focusing on its internal components, a service unit is refined by detailing internal as well as external actions which together accomplish the service delivery process. The BBM is a tool adapted to service design since it supports this refinement.

5. Conclusions and perspectives

This paper displays the design of a pneumatic energy delivery PSS by integrating and adapting existing methods from product- and service-oriented engineering fields. Using models to illustrate the several levels of description (external and functional, process and structure levels) the resulting method enables to engineer a PSS in a system view.

The external interactions of the pneumatic energy delivery system can be identified in both product- and service-oriented perspectives. This provides the external system functions. The functions can be refined through means-end relationships. Sub-functions description through activity scenarios allows defining the time-sequences forming the service delivery process. Two complementary models are used for depicting the component interactions in product- and service-oriented views. Each of the structure models facilitates the iteration at the external and functional level for the component concerned by the perspective provided: the external functional analysis and FBD models are suitable tools for PSS modelling in a product-oriented perspective while the BBM is more convenient in a service design approach. This leads to identify the specifications on components and to a possible refinement during the design process.

Integration and concurrent use of models then allows displaying useful information for both product- and service-oriented perspectives in design, which allows successive refinements adapted to the design process of each object. However, the proposed models are based on a static representation of the system dealing with the structure identification but do not integrate the behavioral aspects of the system over time. The PSS technical design phases have to be supported by simulations models which are not discussed here. Nevertheless, this method provides a working base for the integration of product- and service-based approaches in PSS design.

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